# DEVELOPMENT OF METHODOLOGY FOR DETECTION OF DEFECT LOCATIONS IN PAVEMENT PROFILE

A Thesis

by

SHUBHAM RAWOOL

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2004

Major Subject: Civil Engineering

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Approved as to style and content by:

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| Dan Zollinger<br>(Chair of Committee) | Dallas Little<br>(Member) |
| Nancy Holland<br>(Member) | Paul Roschke<br>(Head of the Department) |

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## ABSTRACT

Development of Methodology for Detection of Defect Locations in Pavement Profile.
(May 2004)
Shubham Rawool, B.E., Goa University
Chair of Advisory Committee: Dr. Dan Zollinger

Pavement smoothness has become a standard measure of pavement quality. Transportation agencies strive to build and maintain smoother pavements. Smooth roads provide comfort while riding, minimize vehicular wear and tear and increase pavement life. A user perceives smoothness of a pavement based on the ride quality, which is severely affected by presence of defects on pavement surface. Defects identified after construction are corrected as per smoothness specifications prescribed by respective transportation agencies. The effectiveness of any method used to determine defect locations depends on the decrease in roughness obtained on correction of defects. Following the above line of thought a method that detects defects by comparing original profile to a smoothened profile will be more effective in identifying defect locations that cause roughness in pavements.

This research report proposes a methodology to detect defect locations on pavement surface using profile data collected on pavements. The approach presents a method of obtaining a smoothened profile from the original profile to help identify defect locations based on deviations of the original profile from the smoothened one. Defect areas will have a higher deviation from the smoothened profile as compared to smooth areas. The verification of the defects identified by this approach is carried out by determining the decrease in roughness after removal of the identified defects from profile. A roughness statistic is used to do the same. The approach is illustrated using profile data collected on in-service pavement sections.

# DEDICATION

*This thesis is dedicated to my parents*

# ACKNOWLEDGMENTS

I wish to extend my sincere thanks and appreciation to all the individuals who have made this work a success.

First and foremost, thanks to my graduate committee chairperson, Dr. Dan Zollinger, for his invaluable guidance, patience, support and encouragement, which has led to the successful completion of this thesis.

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# CHAPTER I
# INTRODUCTION

## General

Over the years, road profile has become a standard measure of pavement quality. Smooth roads provide comfort while riding, minimize vehicular wear and tear and increase pavement life. Stringent measures of smoothness are implemented by transportation agencies to ensure pavement ride quality. Depending on the initial surface smoothness, the contractor either gets a bonus for high quality work that exceeds standards, or penalties for sub-standard work.

A user perceives the quality of a road based mainly on the ride quality. Studies conducted by the American Association of State Highway Officials (AASHO), based on mean panel ratings, showed that subjective evaluation of pavement quality was primarily influenced by roughness.(1) A rough road tends to lead to user discomfort, decreased speed, potential vehicle damage, and increased vehicle operating cost. A user's perception of roughness is based on the vibrations, which he feels while traveling in an automobile. There are different vibrations depending on type of the wavelengths present in the road profile. Vehicles respond with heaving motions corresponding to wavelengths on the order of 15 meters.(2) Heaving motion causes discomfort to a user on account of vibrations due to suspension motion in vehicles. For shorter wavelengths of the order of 1 meter, audible noises involving acoustics of vehicular body are caused.(2) Both are unacceptable as they result in user discomfort. Hence, most of the transportation agencies emphasize adherence to ride quality specifications as one of the criteria in pavement construction. These specifications call for remedial action that may require correction on a pavement surface. Profile data collected on a pavement surface is used to locate defects. Defects in this report are referred to bumps and dips present on a pavement surface. Depending on the location,

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This thesis follows the *Transportation Research Record* format.

the spots for necessary remedial action are determined and repaired to provide a smoother pavement.

Profile of a pavement is a two dimensional slice of road surface taken along the longitudinal direction of a pavement as shown in the Figure 1.[2] The elevation of the pavement surface collected along the length of the section is known as profile data. These elevation measurements are collected using different profile measuring devices which are discussed in subsequent sections. The profile data so collected will show the undulations in the form of defects along the road surface. This data can be modified to generate a smoother profile which can be used as a reference to determine defect locations in a profile.

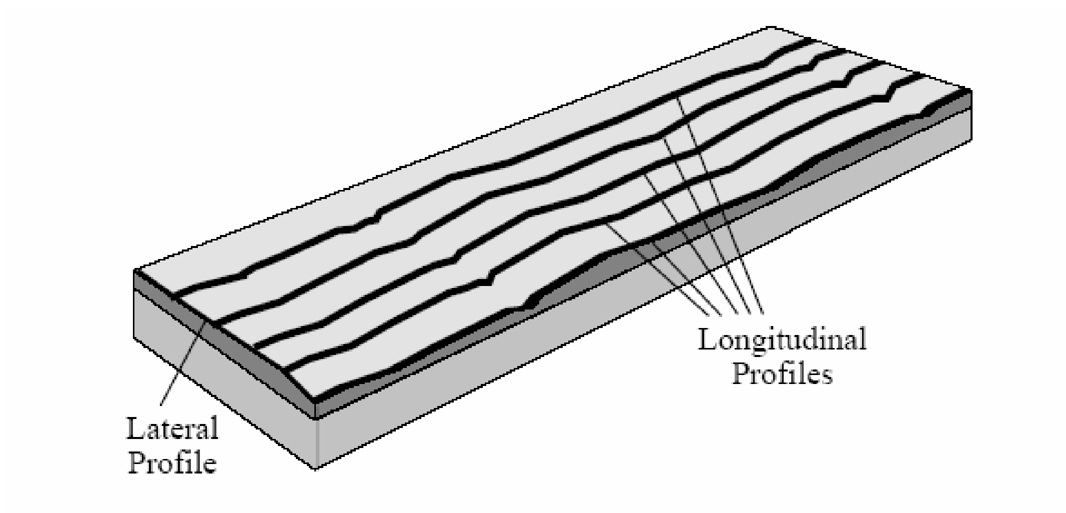


**Figure 1.** A typical road profile [2]

**Research Objectives**

This report proposes a methodology to identify defect locations to improve initial smoothness in pavements. The effectiveness of such a method in determining defect locations will depend on the decrease in roughness obtained on correction of the defects. The decrease in roughness can be quantified using a roughness statistic such as International Roughness Index (IRI) and Present Serviceability Index (PSI).

## Research Methodology

The following tasks summarize the proposed methodology.

*Task 1: Study current methods practiced to determine defect locations*

Two methods reviewed in this report are moving average method and bump template method. Bump template is more widely used method whereas the moving average method is used by the Texas Department of Transportation (TxDOT).

*Task 2: Literature review*

A literature review was done to understand the importance of improving initial smoothness, and to obtain background on devices used for collection of data to be used in analysis. Since the proposed methodology uses IRI gain function as a basis to generate smoother profile, a review of IRI was also performed.

*Task 3: Software development for analyzing profile data*

The proposed methodology is based on detecting defects by comparing original profile to a generated smoothened profile. Rough areas have a higher deviation from the smoothened profile as compared to smooth areas and can be identified by using a threshold value for deviations. A method, based on gain function of IRI that can be used to smoothen a pavement profile is explained in this report. Software to aid in generating smoothened profile and detect defect locations from data collected on pavements is developed as a part of this research.

*Task 4: Application and data analysis*

Profile data collected on in-service pavements is used to illustrate the proposed methodology. The decrease in roughness that may be achieved after removal of the identified defects from pavement profile is also determined. Application of this method using frequency response function for predicted dynamic loads of a quarter truck model is also discussed.

**Existing Methods to Determine Defect Locations**

It is important to detect defects in a pavement profile to provide smoother pavements. At present there is no standard method followed by transportation agencies for detecting defects in a road profile. The following sections describe existing methods that are currently practiced to determine defect locations.

*Moving average Method*

This method uses a moving average filter, which replaces each profile point elevation with the average of several adjacent points. Thus, moving average of pavement profile elevation is obtained along the length of the profile using this filter. Figure 2 illustrates calculation of the moving average of a profile.[2] As shown in Figure 2 the number of adjacent points, to be averaged to obtain the moving average of current position depends on the base length of the filter denoted by B in Figure 2. The current position shown in the figure represents the average of profile elevations present in the shaded area. Such current positions are obtained for all the points along the profile, to obtain the smoothed profile shown in Figure 2. The deviations of the original profile from this moving average smoothened profile are used to determine defect locations.

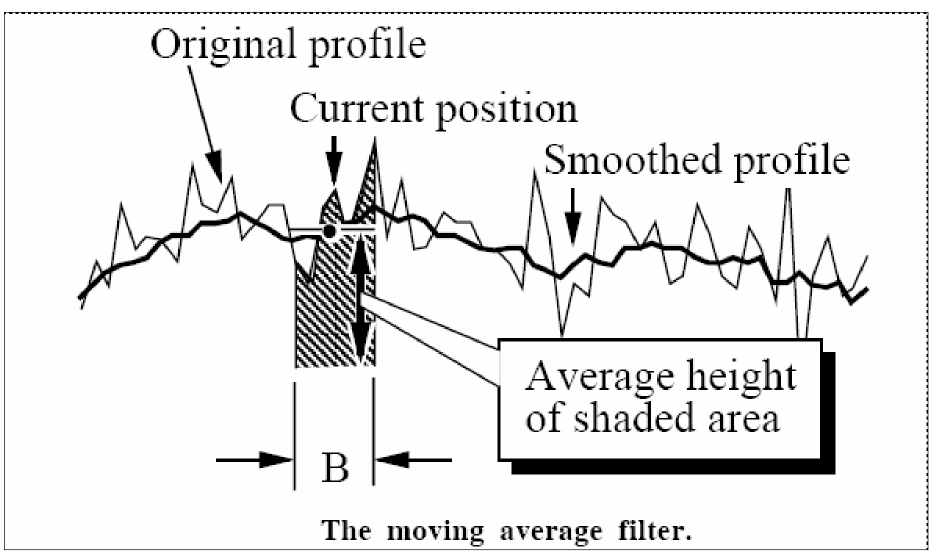


**Figure 2.** Illustration of moving average computations [2]

TxDOT uses this method to detect defect locations. The computer program, Ride Quality, developed by TxDOT is used for quality assurance of pavement smoothness on paving projects. The program uses a base length of 25 feet (B as shown in Figure 2) to obtain the moving average. The idea underlying this method is that rougher areas will have higher deviations from the moving average. The procedure implemented by TxDOT for detecting localized roughness is given in TxDOT's Test Method Tex-1001S, Operating Inertial Profilers and Evaluating Pavement Profiles. At any location, if the deviation of the original profile from the moving average profile exceeds 150 mils, then that location is detected as a defect.

*Bump Template Method*

This method is used when analyzing data obtained from a profilograph. A profilograph generates a trace of pavement profile as shown in Figure 3.

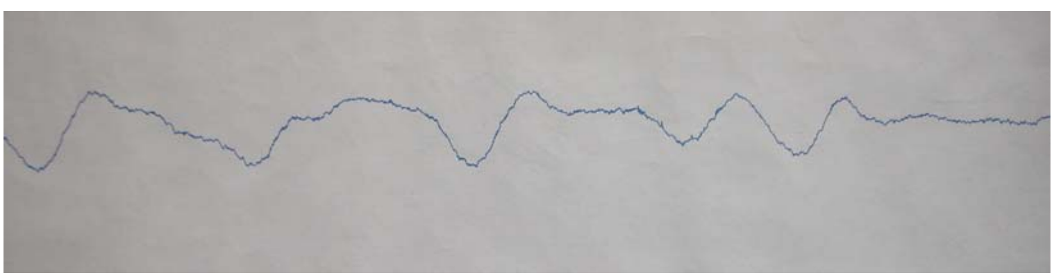

**Figure 3.** A profile trace obtained from a profilograph

Profilograph trace represents the road profile on a scale of 1:300 (1in = 25 feet) in longitudinal direction and 1:1 in vertical direction. The profilograph trace is used to detect defects on a pavement surface. A deviation of 7.62mm (300mils) over a base length of 7.62m (25 feet) is termed as a defect. A typical defect detected, using a bump template, on a profilograph trace is shown in Figure 4.

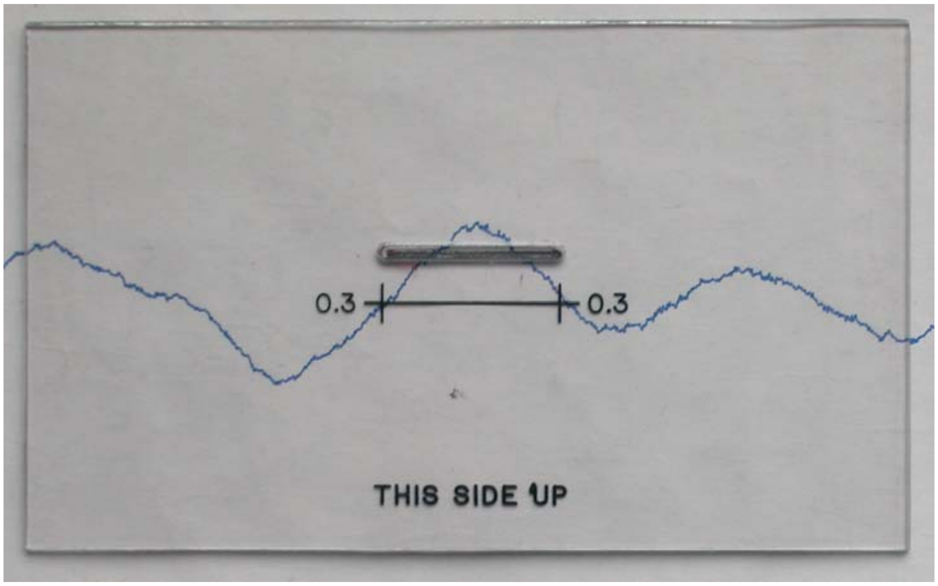


**Figure 4.** Defect detected on a profile trace

The following chapter presents a literature review on the importance of achieving smoother pavements and a brief overview of devices used to collect profile data and indices used to analyze the profile data to obtain a roughness statistic.

# CHAPTER II
# LITERATURE REVIEW

## General

A literature review on the importance of initial smoothness in pavements, different roughness measuring instruments presently used for profile measurements, and roughness statistics used to determine roughness was performed.

## Effects of Initial Smoothness on Pavement Life

Results indicate that initial smoothness has an apparent effect on pavement life.(3) In evaluating the relationship between initial smoothness and pavement life, two different approaches were undertaken.(3) The primary strategy involved the development of models using regression analysis of the available time series roughness data. Each project model was used to predict, for various initial smoothness levels, the service lives associated with the pavement reaching a terminal roughness level. The second approach consisted of analyzing time series roughness data and the corresponding actual pavement failure data for a limited number of pavement segments. Both approaches yielded results indicating that initial pavement smoothness has an apparent effect on pavement life. An analysis was carried out to determine the percent change in life as a function of the percent change in initial smoothness. At the very least, a 9 % increase in life corresponding to a 25 % increase in initial smoothness was observed (Table 1). A 50 % increase in smoothness, was found to increase life, at the very least, by 15 % in most of the cases.

## Effect of Initial Smoothness on Future Smoothness

Design equations developed from AASHO Road Test (1962) imply that initially smoother pavements maintain higher levels of ride quality over their performance period. A study, which analyzed historical roughness data spanning 10 years and representing about 400 sections in Arizona and Pennsylvania, related initial smoothness to long term roughness as illustrated in Figure 5.(4) The relationship observed in Figure 5 is based on Mays Meter roughness index values. Examination of the state highway agency (SHA) data indicated that pavement sections built smoother generally remain smoother over time.[4] In case of pavements of similar design but of different initial smoothness, it is seen that the less smooth sections deteriorate faster (dynamic loading/greater variability in construction) as compared to smooth sections.

**Table 1.** Average percent increase in performance life [3]

| Average percent increase in performance life | | | |
|---|---|---|---|
| Reduction in roughness | 10% | 25% | 50% |
| Alabama PCC | 11 | 28 | 55 |
| Arizona PCC | 7 | 18 | 36 |
| Illinois CRC | 5 | 11 | 22 |
| Minnesota PCC | 6 | 15 | 30 |
| Illinois AC/PCC | 4 | 9 | 18 |
| Alabama AC | 8 | 20 | 39 |
| Arizona AC | 3 | 9 | 18 |
| Minnesota AC | 5 | 11 | 23 |
| PCC is portland cement concrete.<br>CRC is continuously reinforced concrete.<br>AC is asphalt concrete. | | | |

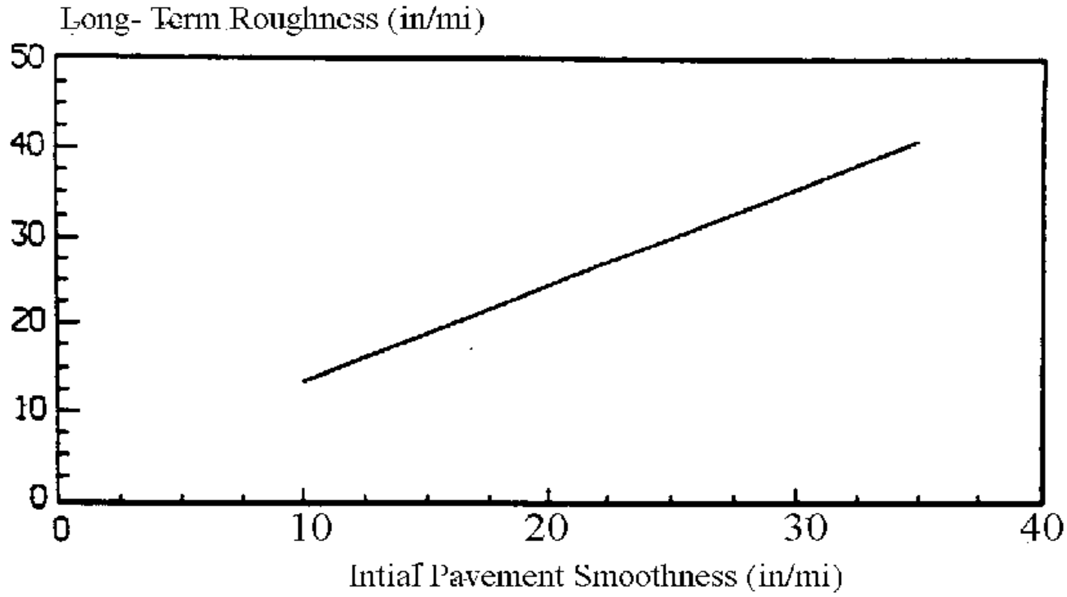


**Figure 5.** Initial pavement smoothness vs. long-term pavement roughness [4]

**Effect of Smoothness on Dynamic Loads**

Unevenness in road surface is a source of dynamic motion in vehicles. The load exerted by the tire of a vehicle fluctuates about the static load carried by the vehicle.[5] The load applied is sum of the static load carried by the tire and a continuously varying load, which can be either positive or negative.[5] Dynamic load simulations at different vehicle speeds were performed for pavements having different PSI values to determine dynamic load effects.[6] Figure 6 presents the maximum and minimum E values (using equation 1[6]) that were obtained for the different pavement sections. It is seen from the figure that as roughness increases i.e. as PSI decrease dynamic loads on a pavement increases.

$$Max\ E = \frac{(Max\ Dynamic\ Load - Static\ Load) \times 100}{Static\ Load} \qquad (1)$$

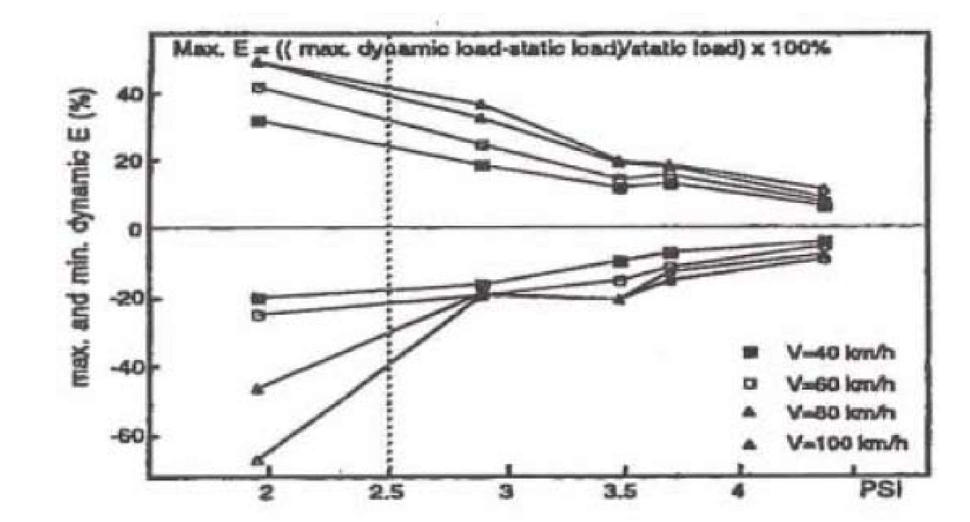


**Figure 6.** Variation of dynamic loads with roughness statistic (PSI)[6]

**Factors Affecting Initial Smoothness in Concrete Pavements**

Smoothness in concrete pavement construction depends on the base type, vertical and horizontal alignment, pavement type, paving equipment and the concrete mixture. Proper attention should be placed on constructing a solid, stable and smooth foundation. A stable and smooth trackline that supports paver tracks or wheels is very important because pavers without automatic grade control unit rely completely on the stabilized trackline for grade control.

During pavement construction stringlines have the greatest impact on pavement smoothness. Srtinglines control the line and grade during placement. Hence care should be taken during placement of stringlines. The size of concrete head in front of the paver should be monitored to make sure that it is neither too high nor too low. A higher head puts additional load on the paver for compacting the concrete. A lower head results in improper compaction and reduction in the strength of concrete. The concrete mix design should be proportioned for correct consolidation without excessive vibration, in order to avoid segregation and vibrator trails which would result in a rougher surface and a lower strength concrete.[7] A steady supply of concrete should be maintained by having a constantly producing batch plant so that paving train moves uninterrupted at a constant speed. Stopping of the paver causes defects on the pavement surface.

### Equipment Used for Profile Measurements

Profile measurements are carried out on pavements on regular basis either to monitor the condition of a road network for pavement management, or to evaluate the ride quality of newly constructed or overlaid pavements. Profile data is collected on pavement using a variety of equipment. The different equipment, that have evolved over the years, can be classified into one of the following categories:

1. Response type road roughness measuring systems (RTRRMs)
2. Profilographs
3. Inertial profilers and
4. Manual devices

RTRRMs devices are housed in automobiles or standardized trailers. Automobile housed systems accumulate the vertical movement of the rear axle of the automobile with respect to frame, while the trailer mounted system accumulate the movement of the trailer with respect to frame. The vertical displacements are accumulated and divided by the distance to report roughness in terms of inches per mile. RTRRMs have certain disadvantages since the measurements obtained from such devices are influenced by vehicle properties such as suspension, tire conditions, tire pressure and vehicle weight. Owing to the above factors the response collected by the device will vary with time and also with the type of vehicle. This has led to replacement of RTRRMs by inertial profilers. Most of the transportation agencies, currently use inertial profilers for data collection. Inertial profilers collect profile data at highway speed and are equipped with computer algorithms to analyze the data during collection. The profile data collected by inertial profilers can also be used to simulate a profilograph over a pavement section, and detect defect locations. Following is a brief discussion on inertial profilers, since the software developed as a part of this thesis uses profile data collected by inertial profiler. Also discussion on profilographs is included.

*Inertial Profilers*

Inertial profilers are used to collect profile data on pavements at highway speeds. The profilers measure surface elevations of pavements using non contact sensors by combining the following three ingredients: 1) a reference elevation; 2) a height relative to the reference; and 3) longitudinal distance.(8) A schematic diagram of an inertial profiler is shown in Figure 7. (5)

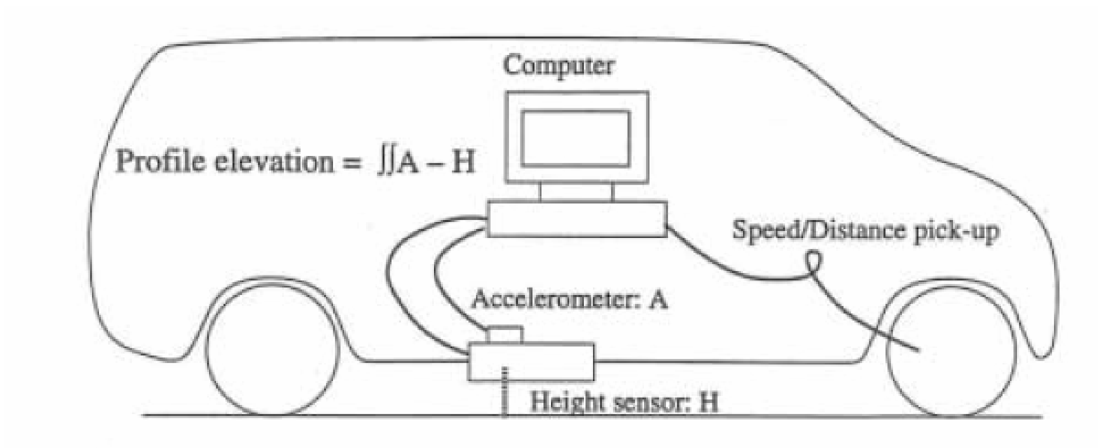


**Figure 7.** Components of an inertial profiler (5)

All the inertial profilers presently available are based on the inertial profiler design originally developed by Sprangler and Kelly at the GMR Laboratories.(9) The principal components of any inertial profiler are height sensor, accelerometers, distance measuring system, and computer hardware and software for computation of the road profile.(5) The height sensors record the distance between the pavement surface and the vehicle. The accelerometers located on top of the height sensors measure the vertical acceleration of the vehicle. The distance measuring system measures the distance traveled from a starting reference point. Using the data obtained from the height sensor, accelerometer and distance measuring system, computer algorithms compute the profile of a pavement surface.

Current manufacturers of inertial profilers include Dynatest, Ames Engineering, International Cybernetics Corporation (ICC), Infrastructure Management Services

(IMS), Surface Systems and Instruments, Pathway and Roadware. Light weight inertial profilers are also available to record profile measurements on newly constructed pavements. The profiling system in light weight profilers is same as that in inertial profilers and is installed in a light vehicle such as a golfcart or an all terrain vehicle. These profilers have very low operating speeds and are usually used for quality control/quality assurance of pavement smoothness in Texas.

*Profilographs*

Profilographs consist of a rigid beam or frame with support wheels at either end and a centre wheel. The support wheels at the ends establish a datum from which the deviations of the centre wheel can be evaluated.[5] A strip chart recorder or a computer records the deviations of the centre wheel with respect to the end wheels. The data recorded in case of a strip chart is analyzed manually to obtain PI and defect locations. However a scanner based system is available called, ProScan, that permits the automated analysis of manual profilographs. A profilograph with an onboard computer, records and analyses data in the field immediately after the tests, thus eliminating the need for manual analysis of data.

The different types of profilographs currently in use are the California profilograph, the Ames profilograph and the Rainhart profilograph. All these profilographs essentially work on the same principle but differ in support wheel configuration or frame support. Figure 8[5] shows a California profilograph with a beam length of 7.65m (25 ft). There are two support wheel systems at either end of the profilograph. Profiles are recorded to a horizontal scale of 1:300 (1in =25ft). In case of the Ames profilograph, the truss in the California profilograph is replaced by an aluminum beam, whereas Rainhart profilograph differs in the support wheel configuration.

## Roughness Measuring Indices

Interpretation of road profile data obtained from any of the above mentioned devices is carried out using roughness measuring indices, generally known as profile indices. A literature review was carried out to provide background on a number of roughness indices that have been developed. These indices include the international roughness index (IRI), present serviceability index (PSI), pavement damage index and profile index (PI).

*International Roughness Index*

IRI is the most widely used profile index to assess the roughness of a pavement. Significant development in IRI took place in 1982 with the World Bank initiating the International Road Roughness Experiment (IRRE).[10] The research findings of this experiment led the World Bank to publish guidelines for conducting and calibrating roughness measurements. It also included a computer code for calculating IRI from a longitudinal road profile.

**Figure 8.** Truss Type California Profilograph

IRI is a mathematical representation of the accumulated suspension motion of a vehicle, over the distance traveled. Hence it has units of slope and is represented in inches/mile or mm/km. Instead of using a vehicle to obtain the accumulated suspension, IRI is calculated by feeding a measured longitudinal road profile into a quarter car simulation algorithm. Illustration of the quarter car algorithm is shown in Figure 9.[5] As shown in the figure the quarter car model consists of one tire that is represented with a vertical spring, the mass of the axle supported by the tire, a suspension spring and damper, and mass of the body supported by the suspension for that tire.[5] The above components are standardized using *The Golden Car* parameters specified in National Cooperative Highway Research Program (NCHRP) Report 228.[11]

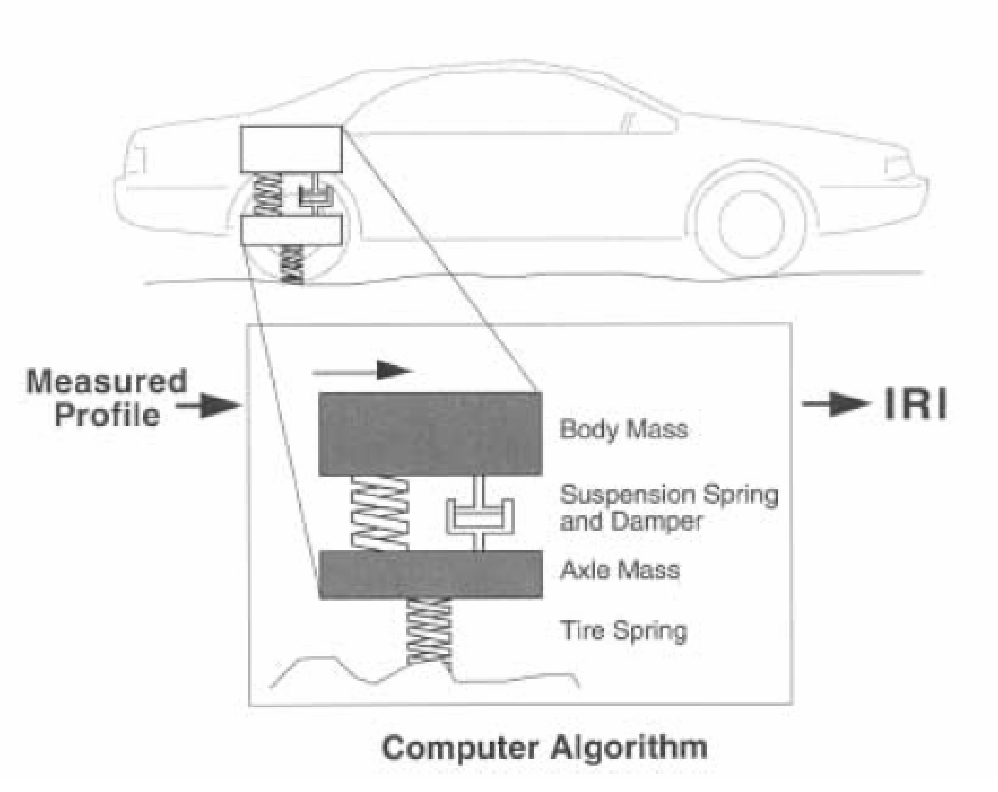


**Figure 9.** Illustration of computer algorithm used to compute IRI [5]

IRI is calculated for a single longitudinal profile. The sampling interval used to collect profile data for IRI analysis should not exceed 300mm for accurate results.[12]

For smooth roads the sampling interval should be reduced for better results. The above conclusions were derived by carrying out interpolation studies to determine what sampling interval represented the original continuous profile of a road. Limits of 300mm for accurate results and 600 mm for less accurate results were set.[12] The profile is smoothed with a moving average whose base length is 250mm. The moving average filter as discussed earlier replaces each profile point with the average of several adjacent points. Hence, it simulates the enveloping behavior of pneumatic tires on highway vehicles and reduces the sensitivity of the IRI algorithm to the sampling interval.[12] The smoothed profile is then filtered using a quarter-car simulation with specific parameter values of *The Golden Car*, at a simulated speed of 80km/hr. The output of the filter represents suspension of the motion of simulated quarter car. The simulated suspension motion is linearly accumulated and divided by the length of the profile to yield IRI. Detailed description of IRI calculations can be obtained from reference 12.

*Present Serviceability Index (PSI)*

PSI is a roughness index which predicts the Pavement Serviceability Rating (PSR), that user a would have assigned to a given pavement section. PSI is reported on a scale from 0-5, with 5 being a very smooth pavement and 0 a very rough pavement. The new PSI model for TxDOT uses an equation that relates spectral characteristics of road profile to PSR. [13] It uses a set of frequencies and their respective amplitudes obtained from profile data to compute PSI. The original PSI model used by TxDOT, was developed from a rating session conducted in 1968-69. [13]

Since its original development over 30 years ago, several changes have taken place that motivated TxDOT to conduct a project for the purpose of evaluating the PSI model. These changes include:

- Improvement in vehicle suspension and handling characteristics;
- More fuel efficient mid-size and compact cars compared to the predominanatly large automobiles used in late 1960s;

- Migration from the response type roughness measuring devices used by TxDOT in the late 1970s and early 1980s, to the inertial profilers that are now standard within the department; and
- Smaller interval of 0.1 mile (in lieu of 0.2 miles) used to report PSI in the current pavement management information system (PMIS).

Thus, TxDOT funded a project with the University of Texas at Arlington and the Texas Transportation Institute to evaluate the current model. Researches conducted ride panel ratings and a new model was developed. The new model uses a fixed set of frequencies associated with a set of fixed equally spaced wavelengths bands, from one to eight meters. (13) The independent variables, the power spectral estimate for each run, are calculated and then averaged over the same section. These estimates for each of the eight frequencies are computed directly from the Discrete Fourier Transform (DFT) in accordance with the following equation. (13)

$$X(t) = \sum_{k=0}^{N-1} X_k e^{-j2*pi*k*f*t} \quad , \; 0 \le f \le 0.5/T \qquad (2)$$

where N = 64, f = 1/8,2/8,,….1 cycles/meter frequencies, and X(t) is the spectral component associated with the frequency.

PSI is obtained using the following equation (13)

$$PSI = 5e^{-\sqrt{\alpha P}} \qquad (3)$$

where $\alpha P$ is as follows

$\alpha P = \alpha_1 P_1 + \alpha_2 P_2 + \ldots\ldots + \alpha_8 P_8$

where each P term represents a power spectrum for each frequency component and “α “ coefficients are derived from the regression analysis.

*Pavement Damage Index*

Fernando(14) (1998) proposed a pavement damage index, Δ, to evaluate acceptability of inertial overlay smoothness based on predicted pavement life.

Pavement response is directly tied to axle load magnitudes and hence it is logical to expect that the dynamic axle load variations will lead to differences in predicted pavement life.(14) In his study Fernando (1998) related the variability in applied surface loads to pavement performance. The dynamic load variability was evaluated by simulating the response of the standard 80 kN single axle to the measured profile, using a two-axle planar model.(14) The pavement damage index was developed to estimate the predicted change in overlay service life due to departures from the target profile, established in the design stage, and the as built profile. The damage index is defined by the following equation. (14)

$$\Delta = \left[\frac{1+zCV_0}{1+zCV_1}\right]^n - 1 \qquad (4)$$

where,

$CV_0$ = coefficient of variation of the applied dynamic wheel loads associated with the target profile

$CV_1$ = coefficient of variation of the applied dynamic wheel loads associated with the as built profile

z = the number of standard deviations corresponding to a given percentile of the predicted dynamic load distribution; and

n = the exponent of Paris-Erdogan crack growth law (for more details see reference)

The reader is referred to the report by Fernando (1998) (14) for the derivation of Eq.(4). This equation provides a rational method for evaluating the quality of finished surface on the basis of predicted performance. In practice, the coefficient of variation in Eq.(1) is determined by vehicle simulation using the measured profile. Note that, $\Delta$, is related not only to the surface profile but to vehicle suspension and geometric characteristics, which all affect the variability in the applied dynamic wheel loads. The benefit of reducing this variability on predicted pavement life is readily apparent from Eq. (4). If $CV_1 < CV_0$, the predicted index is positive, indicating a predicted increase in pavement life with a smoother surface. Note that the reduction in wheel load variability is achieved not only by building smoother pavements but also by designing, manufacturing, and encouraging the use of trucks with improved dynamic performance. If the as-built and target profiles are the same, $CV_1 = CV_0$, and the predicted $\Delta$ is zero, indicating that the as built surface meets the predicted service life associated with the target smoothness. Finally, if the as-built surface is rougher than the target, i.e., $CV_1 > CV_0$, $\Delta$ is negative indicating a reduction in the predicted pavement life because of the expected higher impact loading.

For the purpose of evaluating the performance index, the dynamic load corresponding to a given percentile of the load distribution is used to characterize the magnitude of impact loading. This stems from the spatial repeatability of vehicle dynamic load which has been reported in the literature by Cole and Cebon (1992) [(15)] and by Papagiannakis et.al (1990). [(16)] Experiments with instrumented vehicles have revealed repeated patterns in heavy vehicle dynamic loading which show that loads higher than static tend to recur at specific points along the pavement. This indicates that pavement failure is likely to be determined by peak dynamic forces rather than by average or root mean-square values. Consequently, the performance index is evaluated on the basis of a prescribed percentile of the predicted dynamic load distribution given by $z$ in Eq.(4). In practice, different percentiles may be used to evaluate the acceptability of the overlay profile depending on the highway functional class.

Equation (4) also shows that the effect of surface profile on predicted pavement life is tied to the fracture parameter, n, of the bituminous overlay mix. The higher this parameter, the faster the crack propagation through the overlay material under repeated traffic loading. Consequently, the design and production of the mix is also important to building overlays that last their design lives.

*Profile Index (PI)*

The profilograph measurements provide a trace of the pavement profile, which is reduced to a parameter called the PI. It is used to judge the smoothness of the pavement since it essentially represents deviation of a pavement surface from a reference such as blanking band. Blanking bands are used to analyze the profile trace manually. The general procedure followed during manual reduction of profile data includes obtaining deviations above the blanking band and computing the profile index. A blanking band is made of plastic and is 21.2in $\times$1.7in. It has a scale of 1:25 in horizontal direction and 1:1 in vertical direction giving it a span of 528 feet length wise. There is an opaque band 0.2 inch wide at the centre lengthwise which has five parallel scribes, 0.1in apart on either side. The band is placed on the profile so that it blanks out as much of the profile as possible. It is placed such that the scallops are evenly placed above and below the blanking band. The ends of the blanking bands are marked so that the other blanking bands can be properly aligned and the results can be properly checked.

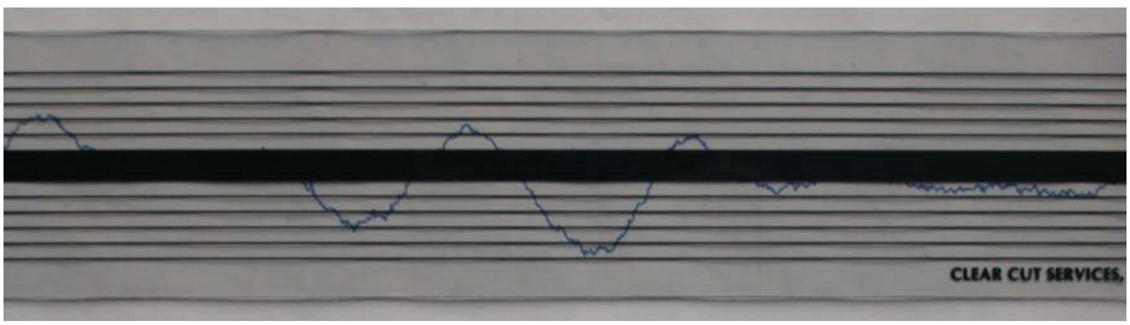


**Figure 10.** Determining PI from profilograph trace

Figure 10 shows illustration of obtaining PI from profilograph trace. Excursions which extend in height more than 0.03in above the blanking band for at least 0.08in in horizontal distance (i.e., 2ft on pavement) are recorded on the profile and rounded to 0.05in. [5] The sum of the recorded heights within the given segment is the profile index (PI) of that segment. PI is expressed in terms of inches per mile. The profilograph trace is also used to detect defects on a pavement surface. A deviation of 7.62mm (300mils) over a base length of 7.62m (25 feet) is termed as a defect (Figure 4). Computer programs are also available to automatically reduce a profile trace. These programs calculate PI's for each 0.1 mile sections and gives details of defect locations.

# CHAPTER III
# DEVELOPMENT OF METHODOLOGY

## General

A road profile can be represented as a summation of sinusoids. Sinusoids essentially are sine and cosine waves defined by their respective wavelengths, amplitudes, and phases. Sinusoids of longer wavelength define the shape of the profile whereas sinusoids of shorter wavelengths are responsible for the undulations in profile. By attenuating or deleting the amplitudes of these shorter wavelength sinusoids a new smoother profile can be obtained. Deviations of the original profile from a new smoothed profile can be used to determine localized roughness/defects present on a road surface. The following sections of this chapter deal with determination of amplitudes and frequencies/wavelengths of different sinusoids present in a road profile and how they can be altered to smoothen or modify the same.

## Distance and Frequency Domain Analysis

Mathematically, a road profile can be represented by adding a number of sinusoids. Consider the illustration in Figure 11[5] where four sinusoids are added together to obtain a road profile. In practice a large number of sinusoids would have to be added to represent a given road profile. As seen from Figure 11, four sinusoids of wavelengths 100ft, 50ft, 33ft and 25ft are added along a length of 100 feet to obtain a profile. The profile plot obtained by adding the above sinusoids is said to be in the distance domain where the longitudinal distance is represented on the x-axis and the vertical y-axis represents the elevation of the profile. A typical profile measurement taken on the road surface would provide us with a similar plot.

The profile thus obtained in the distance domain can be represented in the frequency domain by using the amplitudes and wavelengths of the sinusoids that make up the profile. In our case the wavelengths are 100ft, 50ft, 33ft and 25ft. Let us assume their respective amplitudes to be 1in, 0.75in, 0.5in and 0.25in. Since frequency is reciprocal of wavelength, the frequencies of these sinusoids are 0.01, 0.02, 0.03 and 0.04 cycles/ft respectively.

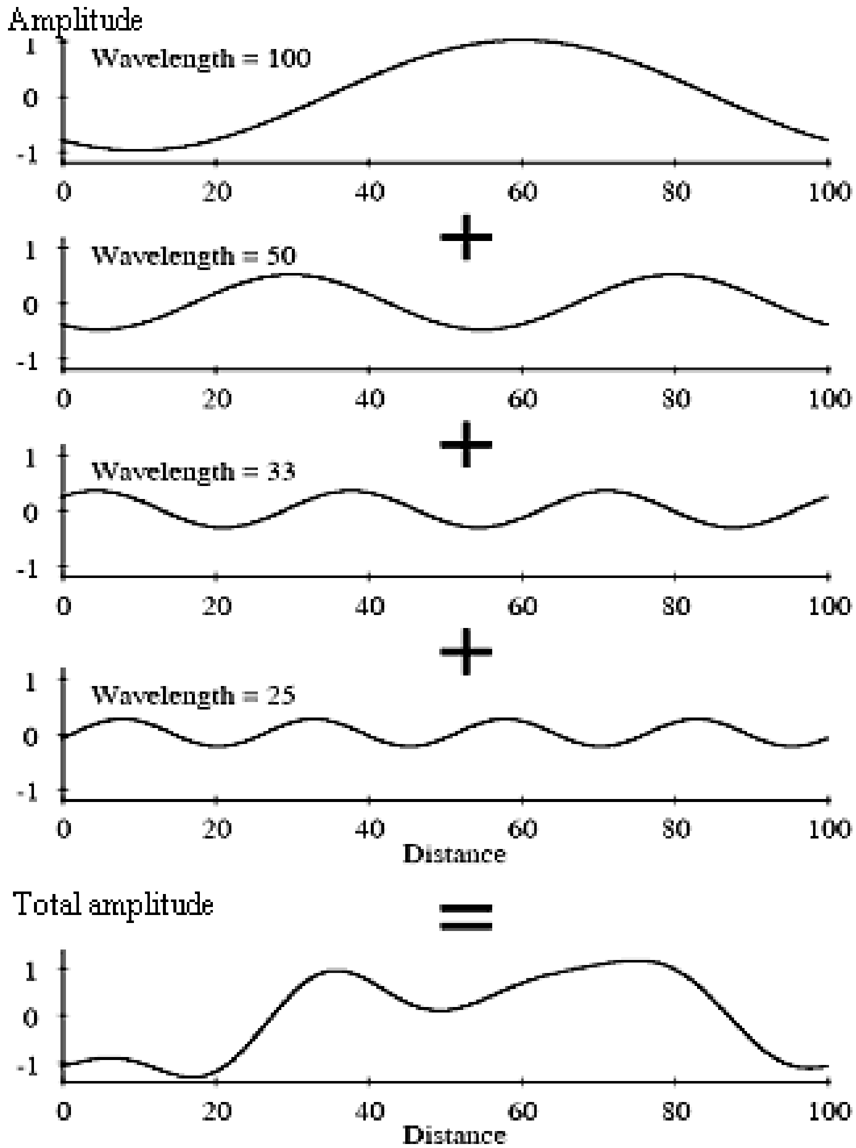


**Figure 11.** Illustration showing addition of sinusoids to obtain a profile [5]

Figure 12 shows us the frequency domain representation of the profile. In frequency domain, the profile is represented with frequency of the sinusoids on longitudinal axis and the amplitude on vertical axis. The frequency domain plot indicates the dominant frequencies present in a profile. There exists a transform known as Discrete Fourier Transform (DFT) that can be used to convert road profile from distance domain to frequency domain and vice-versa.

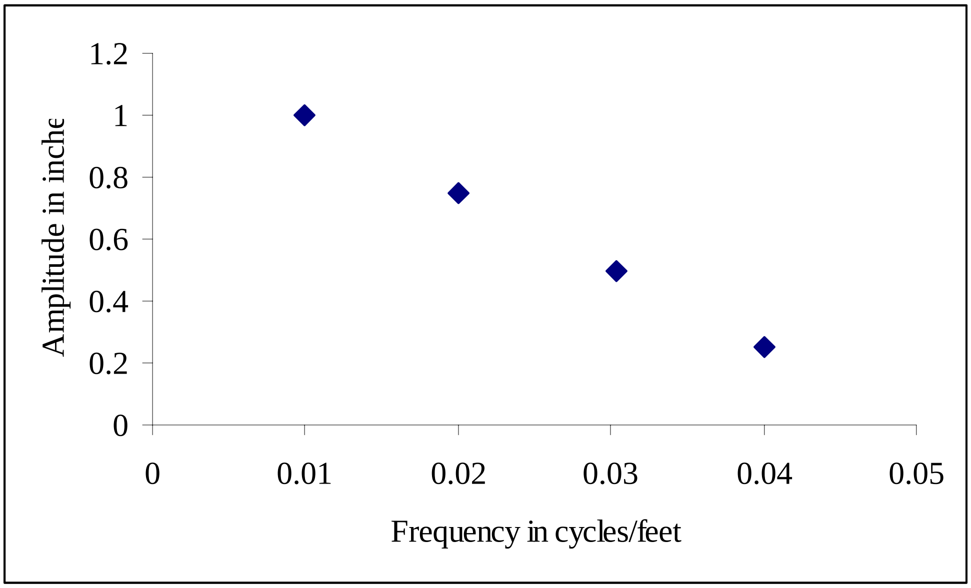


**Figure 12.** Frequency domain representation

**Discrete Fourier Transform (DFT)**

A road profile can be treated as a signal consisting of various frequency components of different amplitudes. DFT can be used to evaluate the frequency content of a road profile and establish the frequencies of sinusoids and their respective amplitudes that make up the profile. The transform used for analyzing road profile is of a discrete nature. A Fourier series in a discrete form is shown in equation 5.[17] For any aperiodic signal x with N points ($x_0$…….,$x_{N-1}$) the DFT is represented as follows

$$x_i = \sum_{u=0}^{N-1}\left[a_u \cos\left(u\frac{2\pi}{N}i\right) + b_u \sin\left(u\frac{2\pi}{N}i\right)\right] \qquad (5)$$

where $a_u$ and $b_u$ are Fourier coefficients.

$x_i$ = profile elevation

N = number of profile elevations/points

i = integer from 0 to N-1

u = integer from 0 to N/2

Conversion of a road profile from distance domain to frequency domain involves determination of $a_u$ and $b_u$. These coefficients can be obtained using equations 6 and 7. (17)

$$a_u = \frac{1}{N}\sum_{i=0}^{N-1} x_i \cos\left(u\frac{2\pi}{N}i\right) \qquad (6)$$

$$b_u = \frac{1}{N}\sum_{i=0}^{N-1} x_i \sin\left(u\frac{2\pi}{N}i\right) \qquad (7)$$

The components $a_u$ and $b_u$ represent the amplitudes of cosine and sine waves that make up a profile. The frequency corresponding to $a_u$ and $b_u$ can be determined using equation 8 (17)

$\omega_u = u/(N\Delta t)$ (8)

where $\omega_u$ = frequency corresponding to integer, u, which ranges from 0 to N/2

$\Delta t$ = Sampling interval at which elevations are collected

The highest frequency that can be obtained using DFT is called the Nyquist frequency and is given by $1/(2\Delta t)$. Figure 13 shows cosine waves having amplitudes a0, $a_1$, $a_2$...... $a_u$ (Nyquist frequency). Left part of Figure 13 shows the distance domain representation where the vertical axis represents the amplitude and the longitudinal axis represents the distance from 0 to N-1 where N is the total number of profile elevations. Right part of Figure 13 shows the frequency domain representation with amplitudes on the vertical axis and frequency from 0 to u (Nyquist frequency) on longitudinal axis. Figure 14 shows similar plots for sine waves having amplitudes $b_1$, $b_2$......$b_u$. It should be noted that the $b_0$ component is always zero in DFT transforms.

Modifying the amplitude components in the frequency domain leads to a change in resultant profile in distance domain. A modified profile can be obtained by substituting new coefficients in Eq.(5). When $a_u$ and $b_u$ are altered in Eq. (5), new elevation points are obtained for a given profile. In a pavement profile, sinusoids with higher frequencies are responsible for roughness. If the amplitudes of these sinusoids are attenuated or deleted, in the frequency domain, then a modified profile with reduced roughness can be obtained, in distance domain. The following chapter discusses about generating a smoother profile by modifying data in frequency domain and utilizing this to identify defect locations in a road profile.

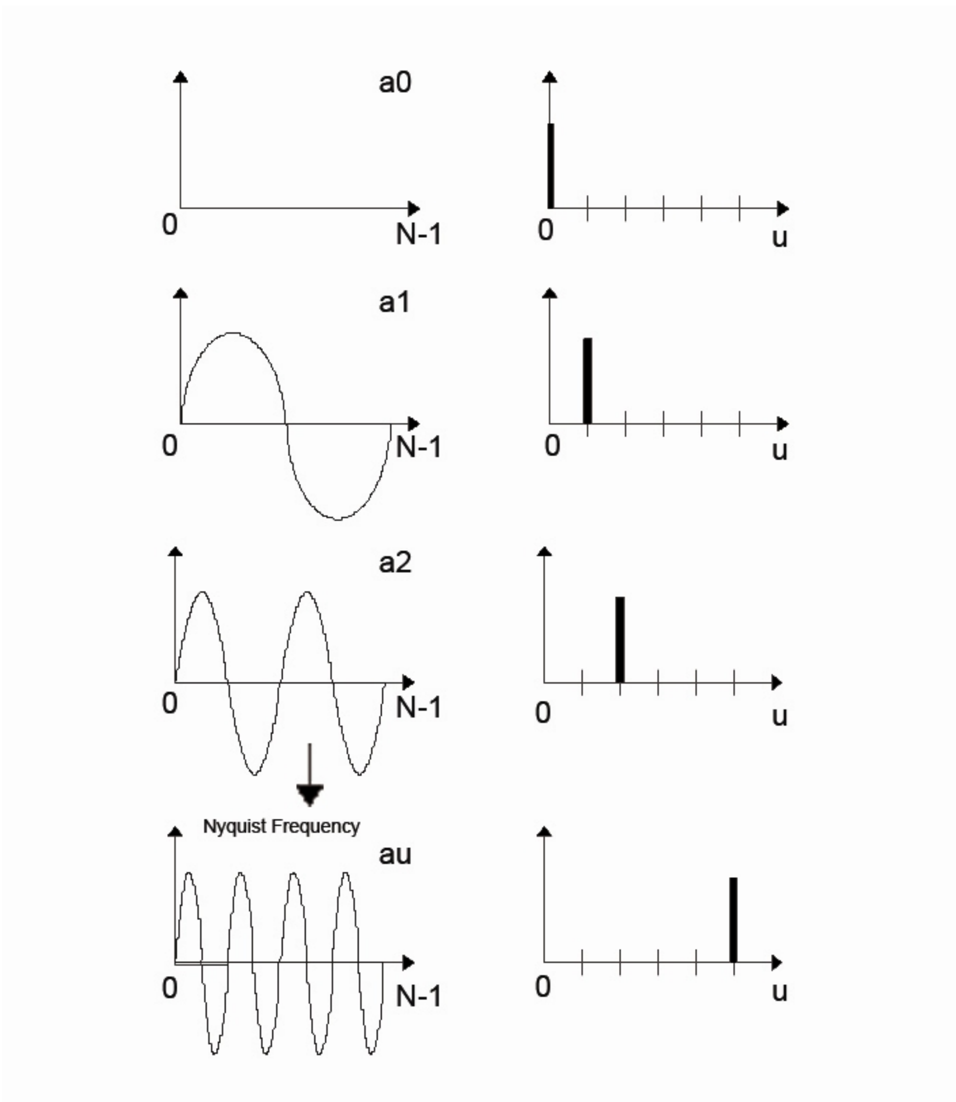


**Figure 13.** Illustration of cosine waves in distance and frequency domain

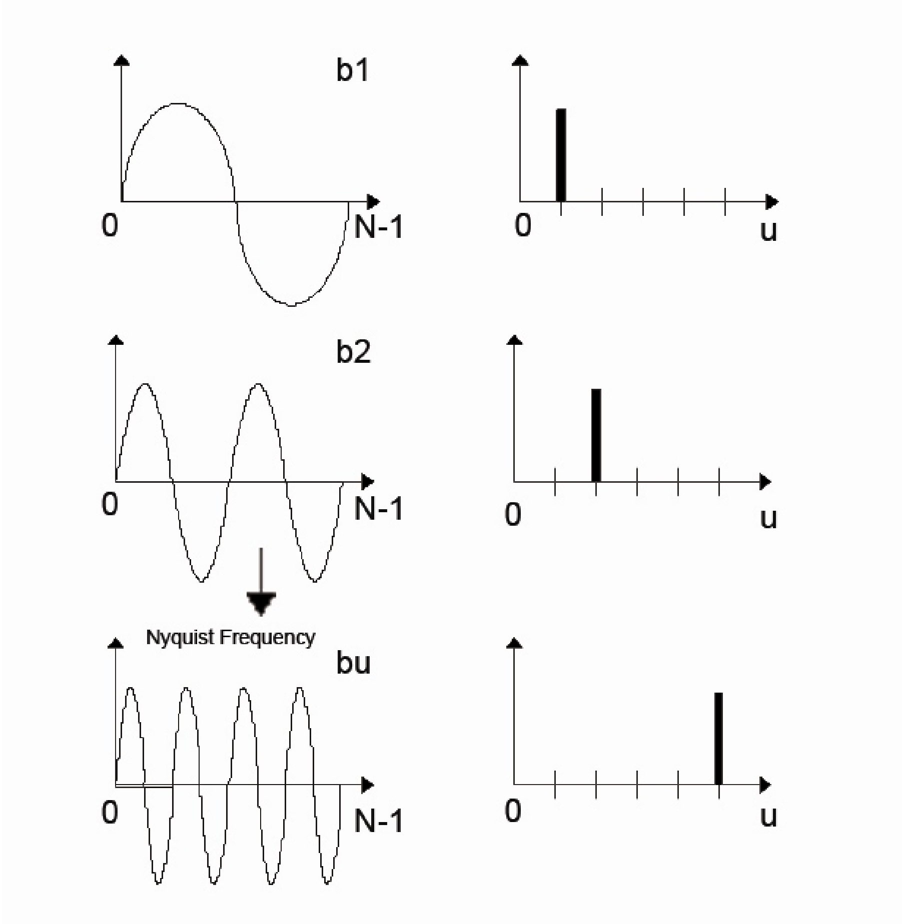


**Figure 14.** Illustration of sine waves in distance and frequency domain

# CHAPTER IV
# SOFTWARE LOGIC AND ILUSTRATION

## General

The Profile Analysis Software (PAS) developed as a part of this thesis, determines the defect locations on a pavement surface. In this chapter, a brief overview of the stages involved in this software, its structure and design concepts are presented. The input to the program is profile data collected by inertial profilers and the output of the program consists of details of identified defects.

## Generating Smoother Profile

Profile data collected by profilers consists of elevations of pavement profile in mils or inches on both the wheelpaths. The elevations are collected at a fixed sampling interval. The sampling interval helps calculate the distance. The input file format used by TxDOT is shown in Figure 15. The first 5 records of the input file give general information about the project on which data are collected. Record 6 onwards consists of pavement profile elevations. For more information on input file format refer TxDOT's Test Method Tex-1001S, Operating Inertial Profilers and Evaluating Pavement Profiles. Roughness statistics, IRI and PSI, are used to determine the roughness of original profile. IRI obtained is expressed in inches/mile and PSI is reported on a scale from 0-5, with 5 being a very smooth pavement and 0 a very rough pavement.

### *DFT Calculations*

DFT calculations give the amplitude and wavelength/frequency of cosine and sine waves present in the given profile. The amplitudes of cosine and sine waves are the Fourier coefficients $a_u$ and $b_u$ respectively and are obtained using equations 6 and 7 from Chapter III. The frequency $\omega_u$, corresponding to the amplitude is obtained using equation 8 from Chapter III. DFT calculations give the frequency domain representation of the profile data.

```
Head3,09262002,17,21,SHOO02S,0000 +00.000,K1
CMET3,ProfilerModel,,,,,123456789,09262002
KPRF01,mil,LR,6,i
Data
Southbound on overlaid section beginning at 200 feet(Comment)
970, 940,0
981, 932,0
992 ,953,0
704,837,0
```

**Figure 15.** Input file format

*Modification of profile data*

Profile data is modified in the frequency domain by removing frequencies above a chosen frequency. Hence forth this chosen frequency will be termed as *cutoff frequency* in this report. Profile data that consists of N number of elevation readings will have N/2 number of frequencies. The aim of modifying profile data in the frequency domain is to obtain a smoother profile by removing frequencies from the profile that are responsible for roughness. To identify the cutoff frequency the gain function of IRI can be used. The gain function gives an idea of frequencies that cause roughness in pavements. Figure 16 shows the gain function of IRI.

As seen from Figure 16, IRI is influenced by wavelengths ranging from 66 in to 875 in (wave numbers ranging from 0.045 to 0.6) since the gain is higher than 1 for these wavelengths. These wavelengths represent a frequency range of 0.0011 cycle/in to 0.0153 cycle/in. To generate a smoother profile, a cutoff frequency closer to 0.0011 cycle/in need to be chosen. After removing the frequencies above the chosen cutoff frequency, the remaining sinusoids (i.e. sinusoids with frequencies lower than cutoff frequency) with their respective amplitudes are fed in Eq.(5) from Chapter III to generate a smoother profile. Also adding the amplitudes of sinusoids at each sampling interval along the distance would result in the same profile as obtained from Eq.(5) in Chapter III.

*Detection of Defects*

The original profile will deviate from the smoother modified profile. These deviations would certainly be more at locations where there is a defect in the profile. Fernando et.al. reported in the literature a deviation of 150 mils to be appropriate to detect potential defect locations.[18] Same magnitude of deviation is used in this methodology to detect defect locations. To locate a defect the difference in elevation between the original and the modified profile (obtained after doing DFT calculations), at every sampling interval is determined.

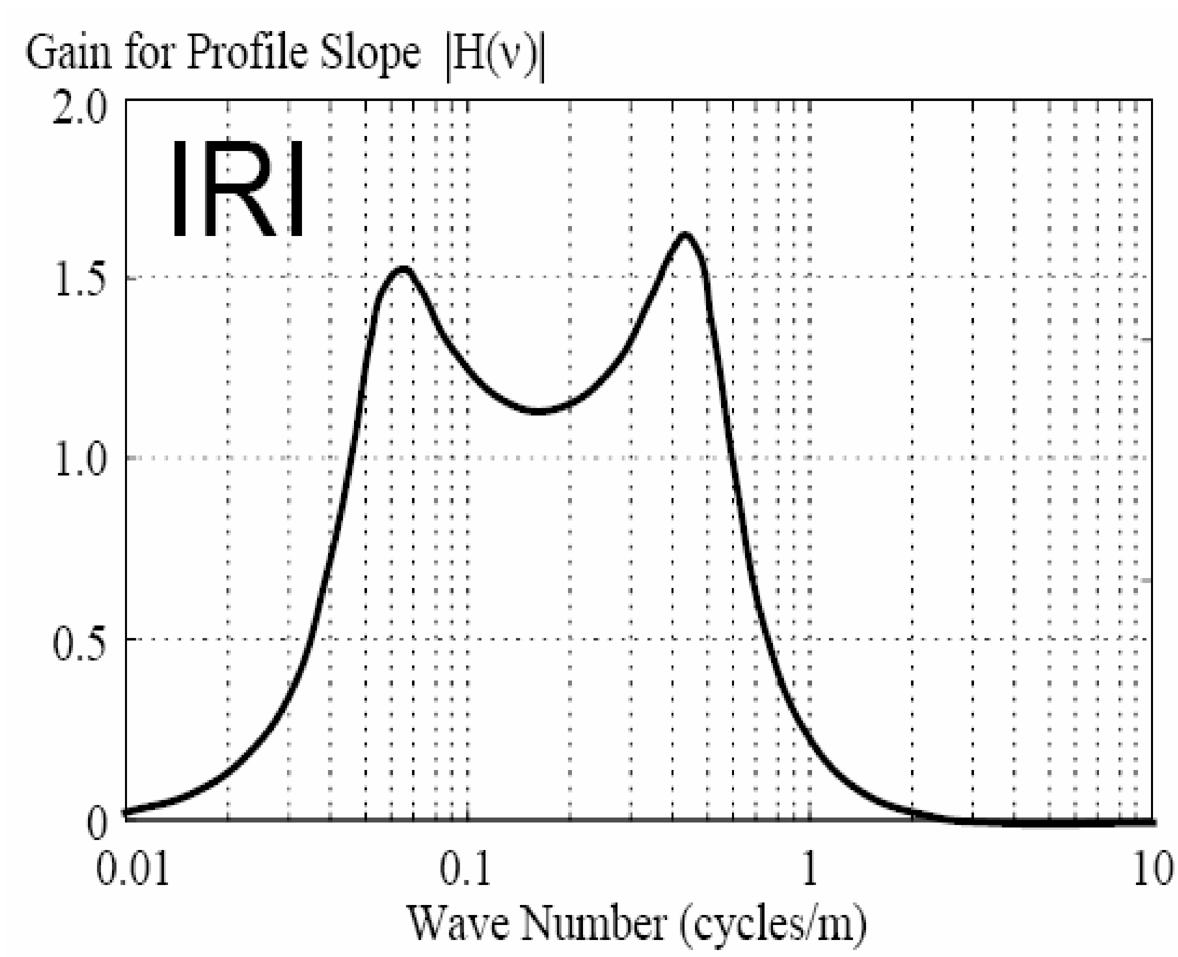


**Figure 16.** IRI gain function [5]

Any location where the difference exceeds 150 mils is identified as a potential defect. [18] This methodology uses the same procedure used in TxDOT Test method 1001S to identify defect locations. If the elevation difference between original and modified profile is greater than 150 mils, then that location is termed as a bump. Similarly if the difference is greater in magnitude than negative 150 mils the location is termed as a dip. Figure 17 shows the output obtained from this program. The output file gives the defect locations in feet, the height of the defect in mils, beginning location, end location and type of the defect (bump/dip). Figure 18 shows the flow chart for the PAS program.

*****C:\Documents and Settings\shubham\Desktop\ Detection Program(1)\1K.PRO*****

File Name:C:\Documents and Settings\shubham\Desktop\output.txt

Header Information

HEAD3,20030513,44,239,US0290 ,0000 +00.000,K1

CMET3,FORD_AEROSTAR_MINI_VAN,10BT,80006MI,MI,1FMDA31U3VZA11901, 20020101

KPRF01,mil,LR,6.335,i

Defect Details are as follows

| Defect no. | Location in miles | Location in feet | Height in mils | Beginning Location | End Location | TYPE |
|---|---|---|---|---|---|---|
| 1 | 1.620 | 8532 | -173 | 8526 | 8541 | DIP |
| 2 | 2.270 | 11992 | 169 | 11983 | 11997 | BUMP |
| 3 | 2.360 | 12450 | -162 | 12443 | 12458 | DIP |
| 4 | 2.440 | 12874 | -234 | 12870 | 12880 | DIP |
| 5 | 2.480 | 13115 | -164 | 13110 | 13119 | DIP |

Total number of Defects is 5

| Section | Original | | Defects removed | |
|---|---|---|---|---|
| No. | IRI | PSI | IRI | PSI |
| 0.1 | 65.879 | 3.78 | 65.879 | 3.78 |
| 0.2 | 49.879 | 4.03 | 49.879 | 4.03 |
| 0.3 | 53.696 | 3.97 | 53.696 | 3.97 |
| 0.4 | 52.1 | 4.01 | 52.1 | 4.01 |
| 0.5 | 48.866 | 4.14 | 48.866 | 4.14 |
| 1.7 | 63.689 | 3.91 | 57.574 | 4.03 |

**Figure 17.** Output file format

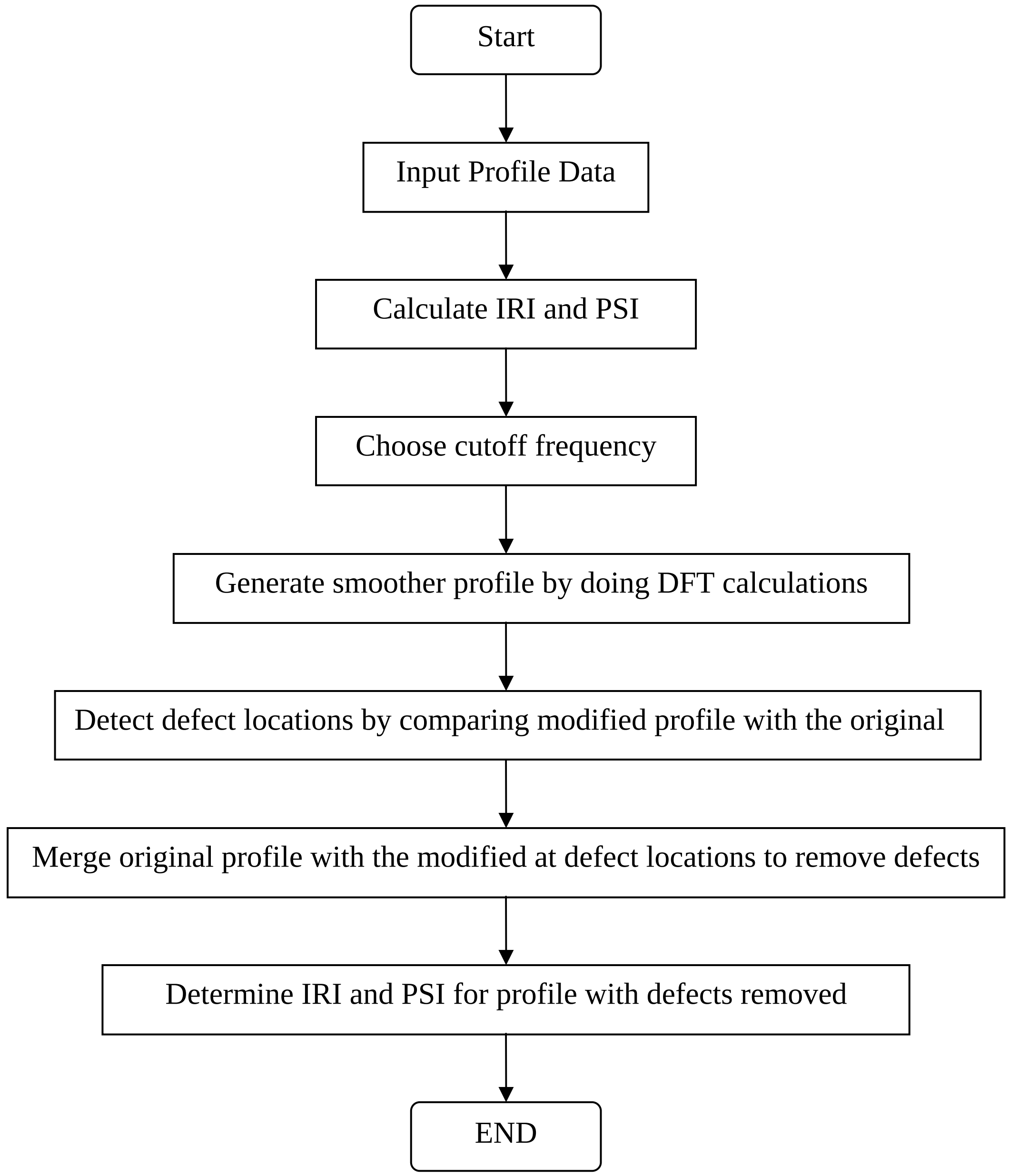


**Figure 18.** Flow chart for PAS program

**Illustration of PAS using Profile Data**

Profile data collected on a 0.1 mile section is used for this illustration. This section has profile data for 528 ft collected at a sampling interval of 6.4 inches. It has around 990 elevation points equally spaced along the length of the section. Since N is 990, N/2 i.e. 495 sinusoids are obtained using Eqs. (6) and (7) from Chapter III. The summation of these sinusoids would result in the original profile. The sinusoids thus obtained have a frequency content ranging from 0.0001576757 to 0.07836484 cycles/in which is obtained from Eq. (8) of Chapter III. Figure 19 shows the profile plot of this section in the distance domain. The elevation measurements of the pavement profile, represented on the vertical axis, is collected using a profile measuring device, such as inertial profiler.

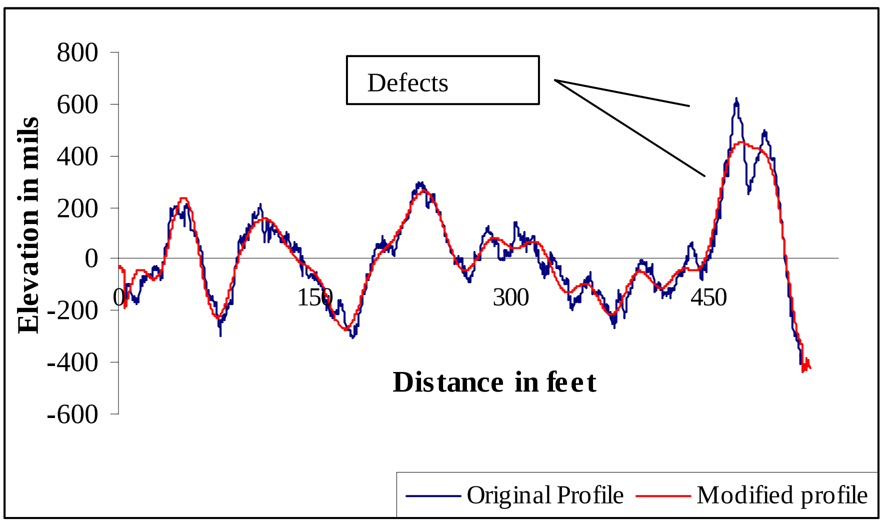


**Figure 19.** Original profile and modified profile

Figure 20 shows the profile plot of the same section in frequency domain. Only frequencies up to 0.02 cycles/in are plotted in Figure 20, since above this frequency the amplitudes of the sinusoids are very small and do not have much influence on the profile roughness. To generate a smoother profile, sinusoids above a chosen frequency are removed. In this case, a cutoff frequency of 0.002522812 cycles/in was chosen. Figure 19 shows a plot of modified profile for the section after removing the sinusoids. Deviation of the original profile from this modified profile is used to identify localized roughness or defects. This analysis was carried out using PAS.

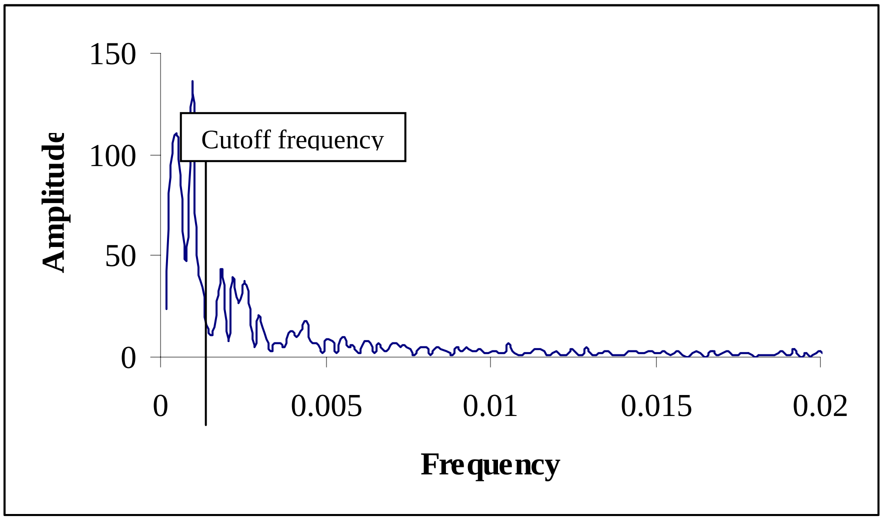


**Figure 20.** Frequency domain plot

As seen from Figure 19 the modified profiles deviates from the original profile. A threshold deviation of 150 mils as reported by Fernando et.al (2002), is used as a criterion to detect defect locations. In Figure 19, the locations marked as defects have elevation difference of more than 150 mils with respect to modified profile. These locations are identified as defects on pavement surface.

# CHAPTER V
# APPLICATION OF PROPOSED METHOD

## General

This chapter discusses the application of this method for identifying defect locations on a pavement surface. Also change in roughness that may be achieved after removal of defects from a pavement profile is determined. For evaluation of this method, profile data collected on 24 pavement sections was used. Out of the 24 sections, 20 sections, each of 0.1-mile length, were analyzed using different cutoff frequencies. This exercise was carried out to determine the range of cutoff frequencies that can be used to determine defect locations. The remaining 4 sections which are more than 3 miles each are analyzed using the same cutoff frequency to evaluate the use of a default cutoff frequency. Also, discussion on application of this method using a cutoff frequency obtained from predicted dynamic load transfer function is discussed. An illustration on determining critical defects in a pavement section with respect to change in IRI, PSI and Coefficient of Variation (CV) of predicted dynamic loads is discussed at the end of this chapter.

## Defect Identification

Evaluation of the method proposed in this report and used in PAS software to detect defect location was carried out using profile data collected on 20 pavement sections each of 0.1 mile length. Each of the 20 sections were first analyzed using TxDOT's Ride Quality 585 software (discussed in Chapter I ) to confirm the presence of defects. Each of the sections had one or more defect locations except for 2. Two sections were so chosen that they did not have a defect to verify that PAS does not detect defects when they are absent in a profile. The cutoff frequency in the range of 0.0012616 to 0.0025228 cycles/in was used to modify profile for all the 20 sections. The cutoff frequency was chosen based on the IRI gain function from Figure 16. The defects identified by PAS were compared with Ride Quality -585. PAS software detected almost identical defect locations as obtained by Ride Quality -585. Also, all the 20 sections were analyzed using a single cutoff frequency of 0.0019 cycles/in to evaluate the use of this frequency as a default cutoff frequency. A default frequency would aid a user to begin profile data analysis which may be then changed by the user after analyzing the obtained results. The defects identified at this cutoff frequency agree well with most of the defects detected by Ride Quality -585. The difference in elevation between modified and original profile for the first and last 5 feet of a section were not compared for this analysis. The details of defect locations for each of the 20 sections analyzed are presented in Appendix B. Number of defects, location of defects, height of defects and type of defect, identified in each of the sections, by PAS and Ride Quality -585 are given in Appendix B.

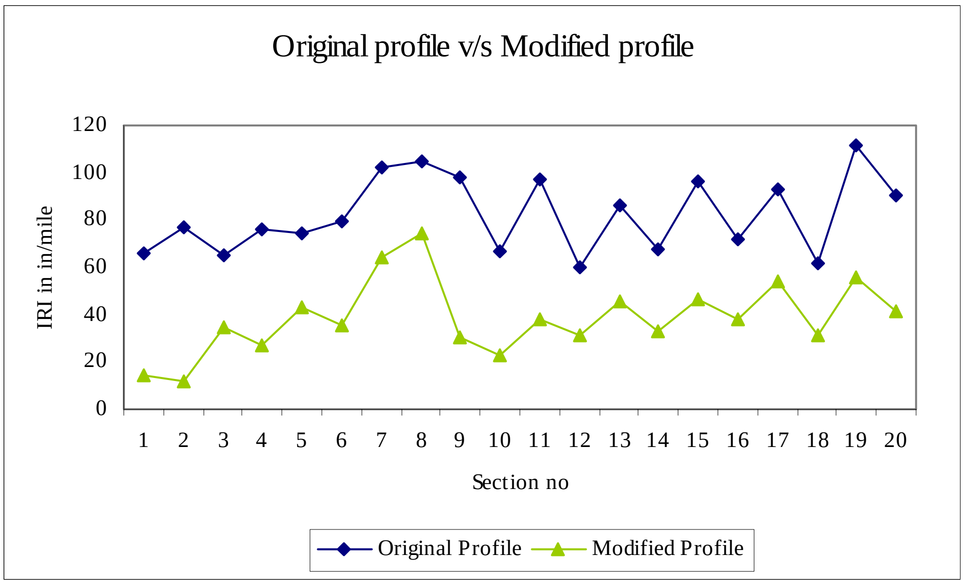


**Figure 21.** IRI of original and modified profile

*Change in Roughness of Modified Profile*

Change in roughness achieved after removing higher frequencies from a profile was determined to illustrate that smoother profile can be obtained from the original profile by removing the higher frequency sinusoids. This analysis was carried out on all 0.1 mile sections. It is seen that considerable reduction in IRI is achieved on removal of higher frequency sinusoids from the original profile. Figure 21 shows reduction in IRI of the modified profile as compared to IRI of original profile for all the 20 sections (refer to Table B2, Appendix B). As evident from Figure 21, high reduction in IRI was attained after modifying the original profile. Cutoff frequencies, chosen for each of the 20 sections, are tabulated in Table B2, appendix B.

*Change in Roughness achieved on removal of defects*

Also reduction in roughness, which can be achieved after correcting the defect locations, was investigated. This analysis was carried out to determine the effectiveness of this method in identifying defect locations that can be corrected to achieve smoother ride. At each of the defect locations identified by PAS, the original profile was changed to converge with the modified profile, on either side of the defect location. The distance on either side of the defect location is determined by comparing the elevation difference between the original and modified profile to determine the width of defect. The locations where the difference falls below 10 mils is considered as the start and end location for a defect. IRI and PSI is calculated for each 0.1 mile section after removal of all the defects, in that 0.1 mile section, to determine the change in roughness that may be achieved after removal of the defects. The following figures illustrate this procedure. Figure 22 shows original profile and the smoothened modified profile for a 0.1 mile section. The section has an IRI of 63.3 in/mi and PSI of 3.91. There are 2 defects identified in this section (Figure 22). Figure 23 shows the profile of the same section with defects removed. The IRI of this section with defects removed is 57.5 in/mi and PSI is 4.03. A 9 % decrease in IRI and 3 % increase in PSI is obtained on removal of the identified defects.

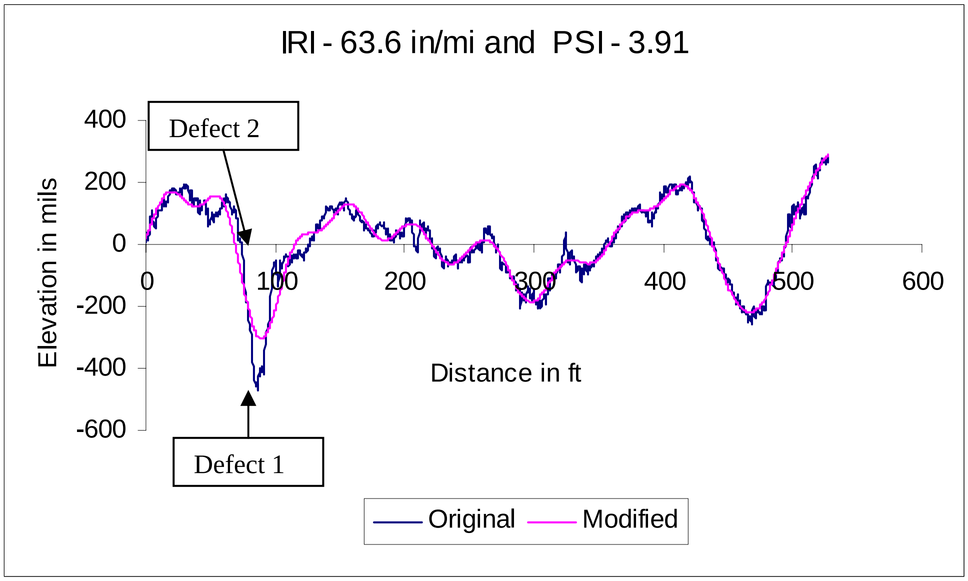


**Figure 22.** Original and the smoothened modified profile for a 0.1 mile section

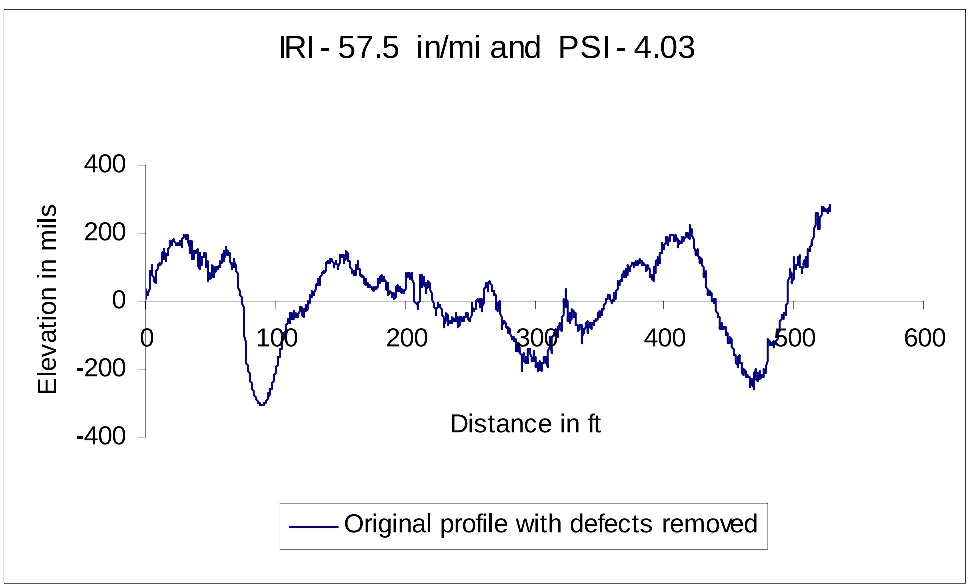


**Figure 23.** Original profile with defects removed for a 0.1 mile section

A comparison of original IRI and PSI and IRI and PSI of the profile with all the defects removed, by the above procedure, shows reduction in roughness for all the sections with defect locations (Figure 24 and 25). This analysis was carried out on 4 sections of more than 3 miles length using a cutoff frequency of 0.0019 cycles/inch and a lead in and lead out length of 25ft. From the results obtained, it may be concluded that this methodology helps identify defect locations that may be corrected to achieve a smoother profile.

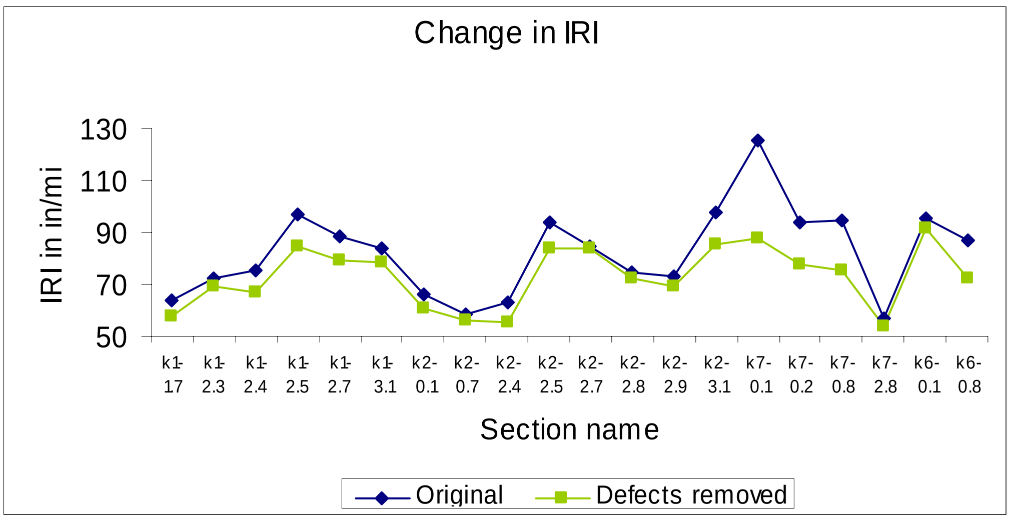


**Figure 24**. Comparison of IRI of original profile and profile with defects removed

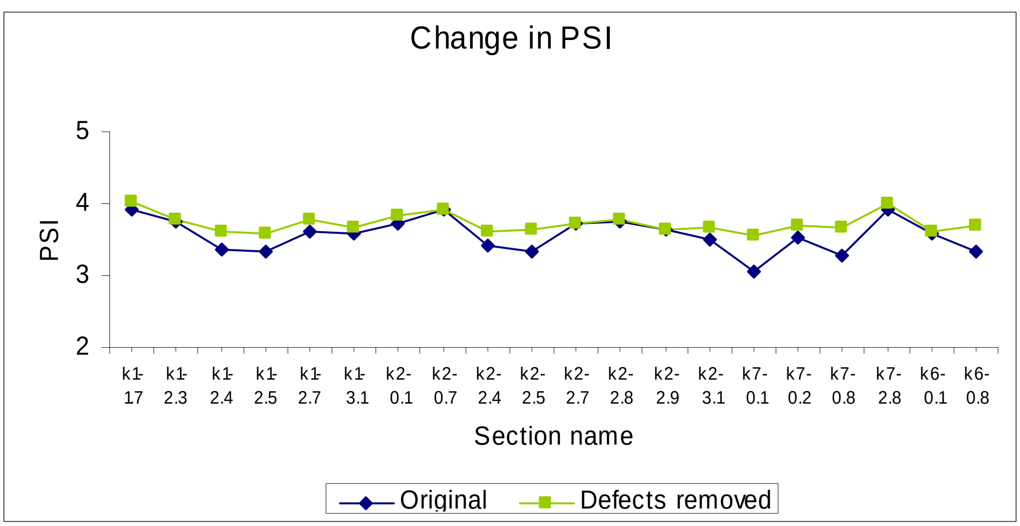


**Figure 25.** Comparison of PSI of original profile and profile with defects removed

**Dynamic Loads on Pavements**

Loads are imposed on pavements at the tire road interface by traveling vehicles. The loads are a combination of static weight of the vehicle and induced dynamic forces. Dynamic forces influence the life expectancy of pavements by speeding up the deterioration process. Following discussion illustrates a method of determining the predicted dynamic loads on a pavement using a simple quarter truck mathematical model. A frequency domain transfer function for predicted dynamic loads is obtained for the quarter truck model. Tire-road interface forces can be obtained from this model by multiplying the profile data with the dynamic load transfer function in frequency domain and then doing a reverse DFT to obtain predicted loads on a pavement. This research was carried out to investigate the frequencies that cause dynamic loads on pavements and determine if the variation in predicted dynamic load on pavement sections is reduced when defects identified are removed from the profile.

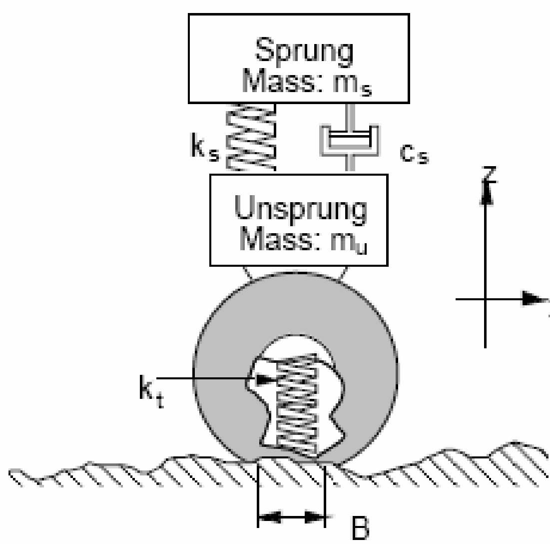


**Figure 26.** Quarter truck model [2]

Figure 26 illustrates a schematic of a quarter truck model. $m_s$ is a fourth of the sprung mass and $z_s$ is its displacement. $k_s$ and $c_s$ are spring and damper, respectively.

$m_u$ is the unsprung mass, which includes the wheel weights, brakes, axles and so forth and $z_u$ is its displacement. $k_t$ represents the spring stiffness of the tire and z(x) represents the roughness displacement By equating the sum of the forces to the mass times acceleration, following two equations of motion are obtained. [19]

$$m_s \ddot{z}_s + c_s(\dot{z}_s - \dot{z}_u) + k_s(z_s - z_u) = 0 \qquad (9)$$

$$m_s \ddot{z}_s + m_u \ddot{z}_u + k_t(z_s - y) = 0 \qquad (10)$$

Tire force is given by equation[19]

$$k_t(z_s - y) = -m_s \ddot{z}_s - m_u \ddot{z}_u \qquad (11)$$

From equation 11 we obtain transfer function for dynamic tire force $F_d$/y as a function of frequency. [19]

$$\frac{F_d}{y} = \frac{k_t w^2 (2k_2 - w^2 + 2icw)}{(k_1 - uw^2)(k_2 - w^2 + icw) - w^2(k_2 + icw)} \qquad (12)$$

where $k_1$,$k_2$,u and c are the constants determined as follows,

$$k_1 = \frac{k_t}{m_s}, \quad k_2 = \frac{k_s}{m_s}, \quad u = \frac{m_u}{m_s}, \quad c = \frac{c_s}{m_s}$$

*w = frequency in radians.*

Sensitivity analysis was carried out to determine the coefficients to be used to generate the dynamic load transfer function that would best represent similar transfer functions published in literature. Following are the quarter truck coefficients that reproduced closest resembling transfer function, using Eq.(12), to that already published[20] (Figure 27). The constants ($k_1$, $k_2$, u and c) obtained from these coefficients agree well with those published by Papagiannakis et at [21]

$m_s$= 22 lb-sec$^2$/in

$m_u$= 3.2 lb-sec$^2$/in

$k_s$ = 2,600 lbs/in

$c_s$= 100 lb-sec/in

$k_t$ = 4,500 lbs/in

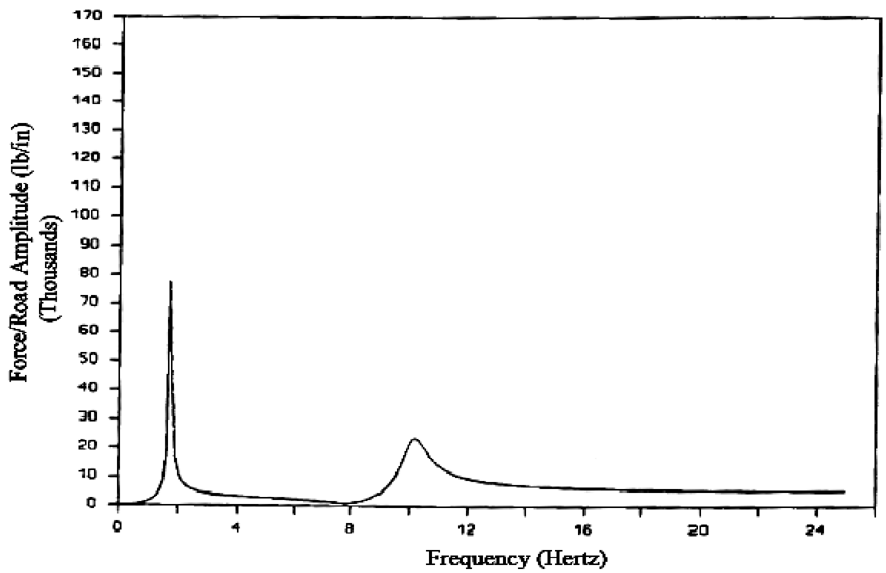


**Figure 27.** Quarter-truck model tire force frequency response (17)

Figure 28 shows the transfer function obtained from equation 12 by using the above coefficients. The dynamic load transfer function is determined at a velocity of 60 ft/sec (equivalent to 41 mph) to compare it with the published transfer function by Todd et.al., which is determined at the same velocity. Though the two transfer functions differ in shape they agree well in determining the first peak frequency and its amplitude responsible for dynamic loads on pavement. This peak frequency can be used to determine the cutoff frequency to identify defects in pavements. Figure 27 has a peak frequency of 0.0025 cycles/in (1.8 Hz) where as the peak frequency from Figure 28 is 0.00195 cycles/in (1.4 Hz). To determine if defects identified by dynamic load criteria (predicted dynamic load transfer function) differ from the ride criteria (IRI gain function), the defects identified at cutoff frequencies lower than the peak frequency of

0.0025 cycles/inch were compared to that identified by default cutoff frequency of 0.0019 cycles/in. It is observed that majority of the defects identified by using cutoff

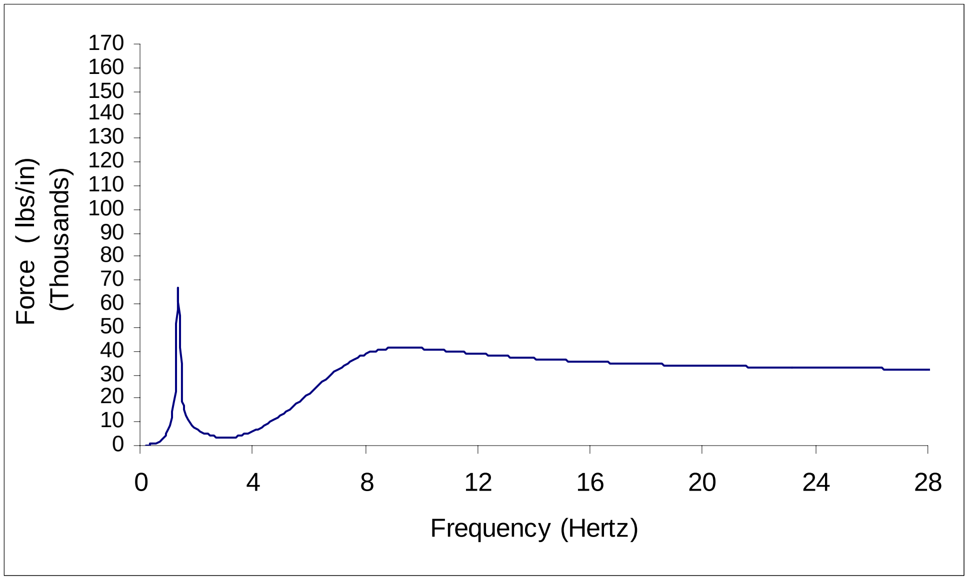


**Figure 28.** Quarter-truck model tire force frequency response obtained from Eq.(12)

frequency of 0.0024 cycles/in are also identified using a cutoff frequency of 0.0019 cycles/in. Hence it may be concluded that the cutoff frequency chosen on the basis of ride takes into account the defects detected using the cutoff frequency chosen from predicted dynamic load transfer function. Comparison of defects detected using cutoff frequency of 0.0024 cycles/in ( > 0.0025 cycles/in) and 0.0019 cycles/in are presented in Appendix B (Figure B19 to B22). Also the dynamic load transfer functions published for a tractor-semi trailer model show a peak frequency of 0.0023 cycles/in. Figure 29 shows measured dynamic load transfer functions for drive axle and leading trailer axle for a tractor-semi trailer model.[22] Since a lower cutoff frequency will always generate a smoother profile, it may be concluded that a cutoff frequency of 0.0019 cycles/in, which is less than those obtained from a quarter truck model or from a tractor-semi trailer is adequate for detection of defects in pavement profile.

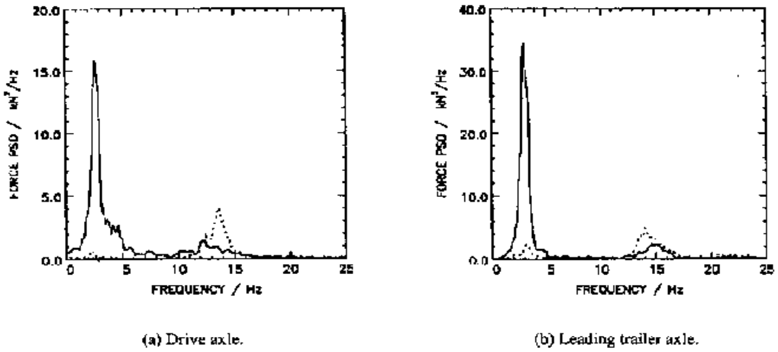


**Figure 29.** Tire force frequency response for tractor semi-trailer [22]

*Determination of predicted dynamic loads on pavement*

The predicted dynamic loads applied by a quarter truck can be obtained by multiplying the road profile with the predicted dynamic load transfer function obtained from Eq.(12) in the frequency domain. Figure 30 illustrates how dynamic loads on pavement can be obtained. Figure 30(a) is profile data in frequency domain. Figure 30(b) is dynamic load transfer function for a quarter truck model in frequency domain. These two are multiplied in the frequency domain and then converted to distance domain to obtain the predicted dynamic loads on the pavement as shown in Figure 30(c).

## Illustration of Determining Critical Defects in a Section

The following example is discussed in this report to illustrate how defects in the same 0.1 mile section can be rated based on their contribution to roughness. For this analysis a 0.1 mile long section having three defect locations was considered. Each defect was then corrected one at a time and the contribution of that defect to roughness was determined by finding the changes in IRI, PSI and coefficient of variation (CV) of predicted dynamic loads. The predicted loads were determined using the transfer function in Eq.(12). CV for this section was determined by dividing the standard deviation of predicted loads by average of predicted loads. The IRI of the original profile without defects corrected is 94.32 in/mile, the PSI is 3.28 and CV of predicted loads is 0.5060. From Table 2, we can see that highest reduction in IRI is obtained by correcting defect number 3, whereas highest increase in PSI and decrease in CV of predicted loads is obtained by correcting defect number 1. This procedure may be used in finding out critical defects in pavements (Figure B23, Appendix B).

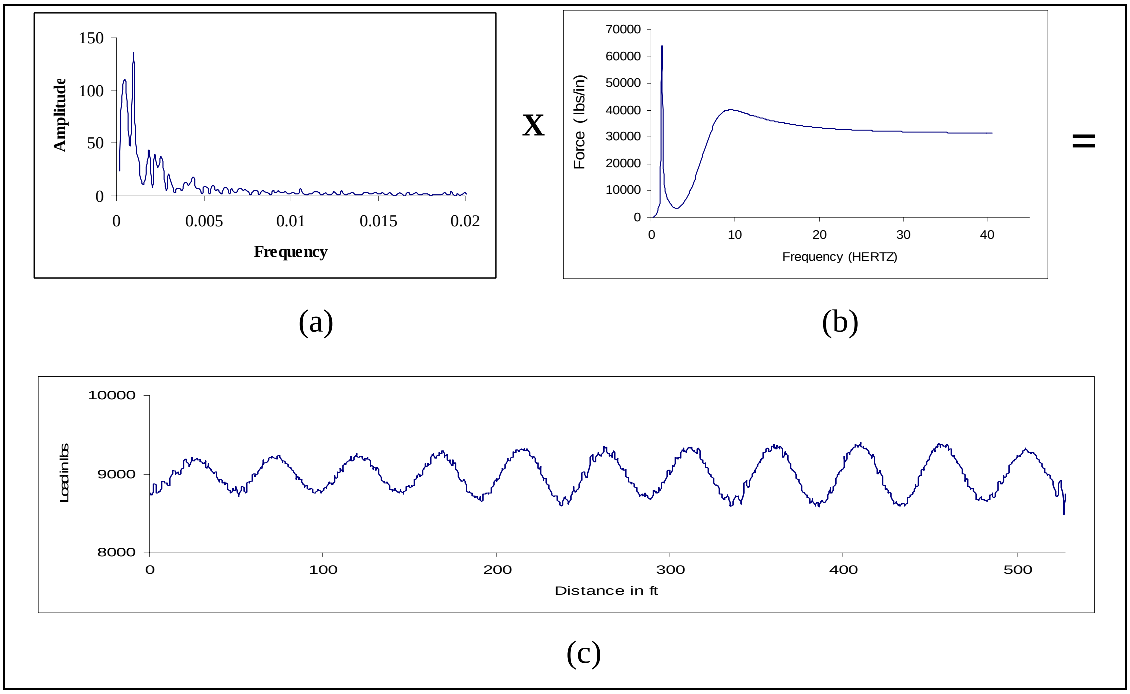


**Figure 30.** Illustration for obtaining dynamic loads on pavement

**Table 2.** Reduction in roughness achieved on removal of defects

| No. | Defect Location in feet | Height of defect in mils | Start location of defect in feet | End location of defect in feet | IRI with defect removed | % change in IRI | PSI with defect removed | % change in PSI | CV with defect removed | % change in CV |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 76 | -157 | 66.5 | 80.2 | 86.72 | 8.05 | 3.5 | 6.70 | 0.4874 | 3.67 |
| 2 | 88.2 | 172 | 80.7 | 96.5 | 91.99 | 2.4 | 3.31 | 0.91 | 0.4929 | 2.58 |
| 3 | 499.4 | 154 | 485.6 | 506.1 | 84.55 | 10.35 | 3.43 | 4.57 | 0.5020 | 0.79 |

# CHAPTER VI
# SUMMARY

## Conclusions

The actual identification of defect is based on the projected decrease in the overall surface roughness, which may be achieved on removal of the defects. Analysis of change in roughness obtained on correction of defects identified by this methodology indicated reduction in roughness. Hence, it can be concluded that this methodology identifies defects that may be corrected to achieve a smoother pavement. Following are the conclusions based on results of different analyses carried out on test sections in this research.

- A decrease in roughness is observed if defect identified by proposed method are removed from the pavement profile. At the defect locations, the original profile was merged with the modified smoother profile obtained after removing frequencies above the specified cutoff. The IRI and PSI of original profile, and profile obtained after merging original profile with the modified at defect locations were compared. All the sections analyzed showed reduction in roughness.

- From the results obtained on analyzed profile data it may be concluded that PAS software, which is developed based on methodology proposed in this report, may be used to detect defect locations in pavements. The proposed methodology uses gain function of a roughness statistic (IRI) as a basis to detect defect locations. This methodology gives user freedom to choose an appropriate cutoff frequency which may be based on gain function of any smoothness index.

- A default cutoff frequency of 0.0019 cycles/in is found adequate to determine defect locations in profile. Defects detected using cutoff frequency of 0.0024 cycles/in based on predicted dynamic load transfer function compared well with defects detected using the default cutoff frequency of 0.0019 cycles/in based on IRI gain function.

Hence, it may be concluded that the cutoff frequency chosen on the basis of this function takes into account the defects detected using the cutoff frequency based on the dynamic load transfer function for a quarter truck model.

**Recommendations**

In this report predicted dynamic loads are determined using a quarter truck model. Further investigation should be carried out to evaluate the feasibility of using a quarter truck model in lieu of complex whole vehicle models. This may be done by running vehicle simulation program to determine predicted dynamic loads for pavement profiles with varying roughness levels. Predicted dynamic loads can be obtained for each axle of the whole vehicle model and for each of the pavement profiles with varying roughness values. Transfer functions obtained from the predicted dynamic loads, for each axle, in this fashion should be compared with the transfer function obtained from the quarter truck model. Procedure for critical defect identification based on the decrease of predicted dynamic loads and decrease in roughness, as illustrated in this report, should be further investigated.

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# APPENDIX A

## Users Guide for PAS defect detection software

The Profile Analysis Software (PAS) developed as a part of this MS thesis, is a collection of 3 programs. Major part of the code is written in Visual Basic 6.0. The code for IRI is in Visual Fortran whereas the code for PSI is in C.

**System Requirements**

The PAS program is written in Visual Basic Version 6.0. It is developed to run in Windows 98, 2000 and XP and occupies around 2 MB of hard disk space.

**Getting Started**

The following section explains about installation and using this program. This manual assumes that user is familiar with Windows. The user can run this program from the disk by double clicking the executable file, pas.exe, in the respective drive. To save this program on the hard disk copy the entire folder and then double click on the executable file, named pas.exe, to get started. Please note that there are supporting files in different formats in the folder which are needed for running the program. The details of files needed for running the program are given in appendix C. A double click on the pas.exe opens the introductory window (Figure A1)

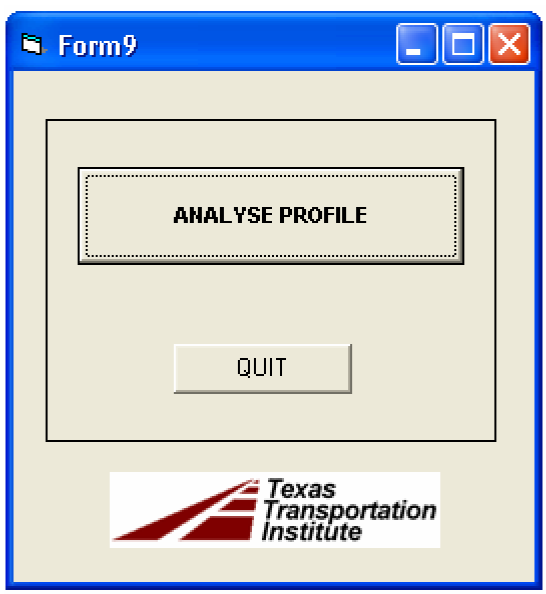



**Figure A1.** Screen 1, Start form.

**Running the Program**

The following sections describe maneuvering through the program. The whole program is designed around a main window form so that it is easy to use. This allows the user to go back and forth from other windows to the main window to modify data. (Henceforth each window form will be termed as screen and numbered in the order in which they appear in the program. For example the introductory form shown in Figure A1 is Screen 1)

***Analyzing Profile Data***

***a)Input:*** Click on the ANALYSE PROFILE button on Screen 1 to open Screen 2 (Figure A2). Click on the FILE button on Screen 2 to open Screen 3 (Figure A3). Screen 3 lets the user choose the input file from any of the directories used for its storage.

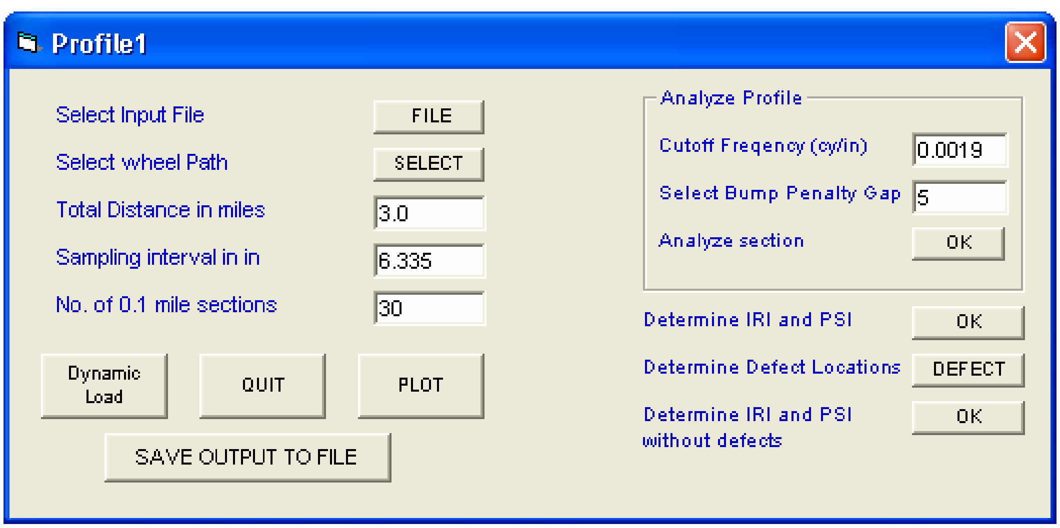



**Figure A2.** Screen 2, Main form

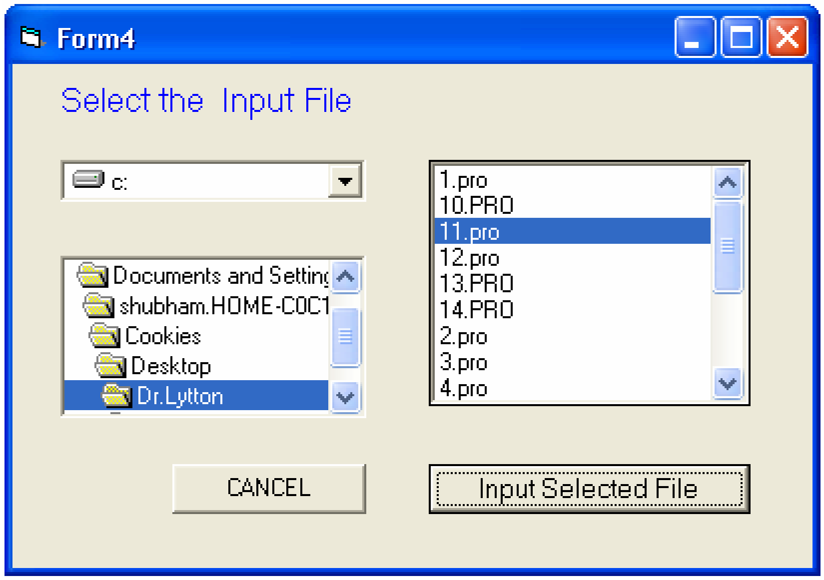



**Figure A3.** Screen 3, Input file select

Select the input file and click on the Input Selected File button to input the file to be analyzed. The data file for input should follow the format specified in TxDOT Test Method Tex 1001S, as illustrated in Figure A4.

Head3,09262002,17,21,SHOO02S,0000 +00.000,K1

CMET3,ProfilerModel,,,,,123456789,09262002

KPRF01,mil,LR,6,i

Data (Comment)

Southbound on overlaid section beginning at 200 feet(Comment)

970, 940,0

981, 932,0

992 ,953,0

704,837,0

**Figure A4.** Input file format

The program reads record 3 and wheel path elevations beginning from record 6. The record 3 has the following variables, each separated by a comma.

Variable 1: Profiler Manufacturer

Variable 2: Unit of elevation. (mil(0.001 in) under current TxDOT practice)

Variable 3: The wheelpath (L for left, R for right or LR for dual wheelpath)

Variable 4: Interval between successive measurements (inches or meters)

Variable 5: Unit of interval (i for inches and m for meters)

***b) Selecting wheelpath:*** Click on the SELECT button on Screen 2 to open Screen 4 (Figure A5). On Screen 4 choose the format of data. Presently, all the data collected by TxDOT have a comment column. If the data is with comment column, click on first option button or else click on the second option button. Enter the lead in and lead out distance in feet on Screen 4. A minimum distance of 25 feet is recommended to be used with this procedure. Chose the wheel path on Screen 4 by clicking on the appropriate option button. The LWP selects the left wheel path, RWP selects the right wheel path and the AVG computes average of the left and right wheel path elevations at each sampling interval.

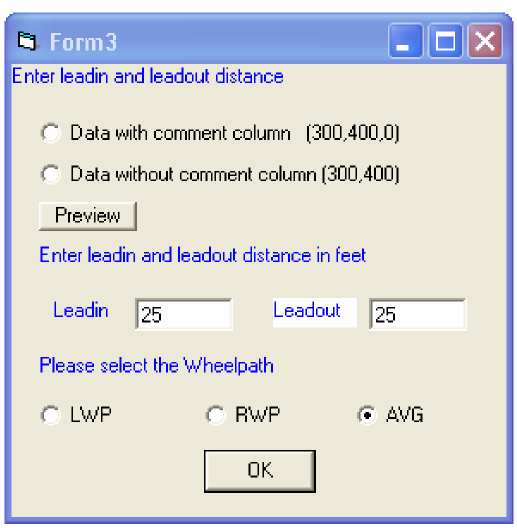



**Figure A5.** Screen 4 Select wheel path

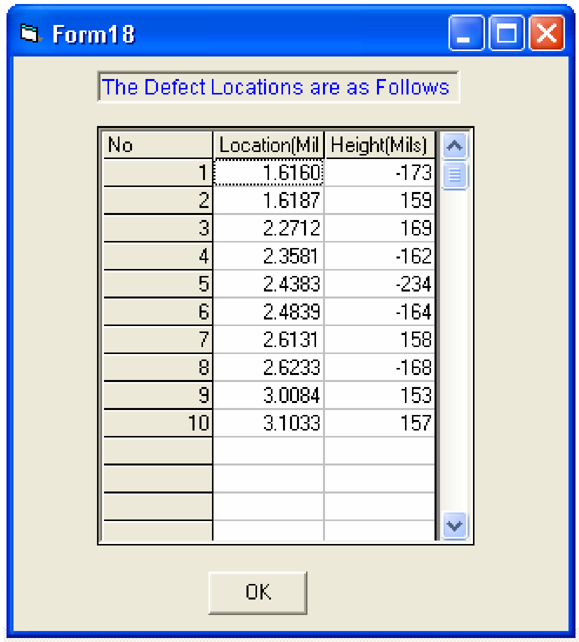
***c) Analyzing Profile data:*** In Analyze Profile section on Screen 2 enter the cutoff frequency to be used to determine defects. All the frequencies above this cutoff frequency are nullified and modified profile is obtained. Enter also the bump penalty gap in feet in this section. Bump penalty gap prevents the software from detecting more then one defect, if present, in the specified gap. The program uses a default cutoff frequency of 0.0019 cycles/in and default bump penalty gap of 5 ft. Click on OK button in this section to generate a modified smoothened profile, calculated using Eq. (6) to (8) from Chapter III for each frequency up to 0.0019 cycles/in. Then the reverse DFT is carried out to generate the modified profile.

***d) Determine IRI and PSI for Original Profile:*** Click OK button next to "Determine IRI and PSI" text box on screen 2 to determine the IRI and PSI for every 0.1 mile section length.

***e) Determine Defect location:*** Click on DEFECT button on screen 2 to determine defect locations in the original profile. The DEFECT button on screen 2 opens screen 5 as shown in Figure A6. The table on screen 5 gives the location of each defect in miles and its height in mils.

***f) Determine change in roughness:*** The change in roughness that can be obtained after removing the defects can be determined by clicking the OK button next to "Determine IRI and PSI without defects" text box.

***g) Saving Output:*** To save the output of profile data analysis, click on SAVE OUTPUT FILE button on Screen 2. This opens Screen 6 (Figure A8) and lets user choose a file name to save the output. The program saves output of the location of defects (start, end and peak location for each defect) and the type of defect. The IRI and PSI of original profile and profile with defects removed is also saved for every 0.1 miles. The output file also contains header card information of the input file. The format of a typical output of data analysis is shown in Figure A7.



Form18

The Defect Locations are as Follows

| No | Location(Mil | Height(Mils) |
|---|---|---|
| 1 | 1.6160 | -173 |
| 2 | 1.6187 | 159 |
| 3 | 2.2712 | 169 |
| 4 | 2.3581 | -162 |
| 5 | 2.4383 | -234 |
| 6 | 2.4839 | -164 |
| 7 | 2.6131 | 158 |
| 8 | 2.6233 | -168 |
| 9 | 3.0084 | 153 |
| 10 | 3.1033 | 157 |

OK

**Figure A6.** Screen 5 Defect location form

*****C:\Documents and Settings\shubham\Desktop\ Detection Program(1)\1K.PRO*****

File Name:C:\Documents and Settings\shubham\Desktop\output.txt

Header Information

HEAD3,20030513,44,239,US0290 ,0000 +00.000,K1

CMET3,FORD_AEROSTAR_MINI_VAN,10BT,80006MI,MI,1FMDA31U3VZA11901,2002

KPRF01,mil,LR,6.335,i

Defect Details are as follows

| Defect no. | Location in miles | Location in feet | Height in mils | Beginning Location | End Location | TYPE |
|---|---|---|---|---|---|---|
| 1 | 1.620 | 8532 | -173 | 8526 | 8541 | DIP |
| 2 | 2.270 | 11992 | 169 | 11983 | 11997 | BUMP |
| 3 | 2.360 | 12450 | -162 | 12443 | 12458 | DIP |
| 4 | 2.440 | 12874 | -234 | 12870 | 12880 | DIP |

Total number of Defects is 5

| Section No. | Original IRI | Original PSI | Defects removed IRI | Defects removed PSI |
|---|---|---|---|---|
| 0.1 | 65.879 | 3.78 | 65.879 | 3.78 |
| 0.2 | 49.879 | 4.03 | 49.879 | 4.03 |
| 0.3 | 53.696 | 3.97 | 53.696 | 3.97 |
| 1.7 | 63.689 | 3.91 | 57.574 | 4.03 |

**Figure A7.** Output File Format

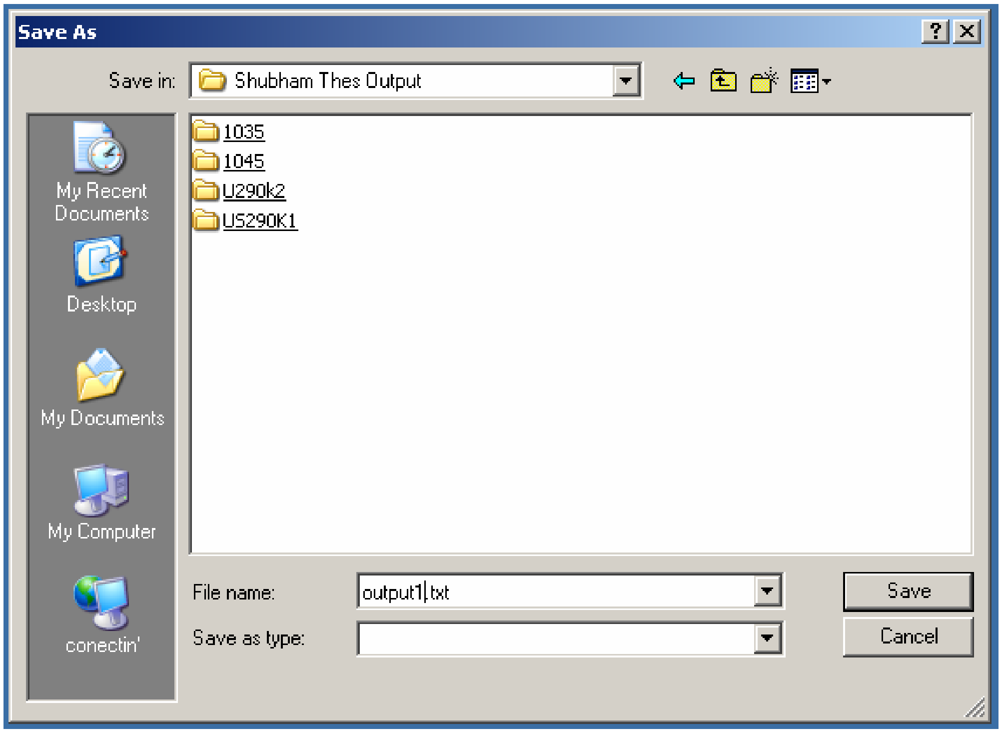



**Figure A8.** Screen 6, Save Output

***e) Graphical Plots:*** Graphical plots let the user view the difference between the original and modified profile and the profile with defects removed. Click on PLOT button on Screen 2 to open Screen 7 (Figure A9) Click on the section number to view profile plot for that particular section. Text boxes on Screen 7 also give information of the IRI and PSI of original profile and profile with defects removed. Original profile is plotted in green, the modified profile is plotted in yellow and profile with defects corrected in red. The details of beginning, end and peak locations of the defect in feet and height of defect in mils are reported in the table on Screen 7, if defects are detected in the chosen 0.1 mile section.

***Determining Dynamic Loads***

***a) Determining transfer function***

Click on Dynamic Load button, on Screen 2, to open screen 8 (Figure A10). Screen 8 lets user enter the quarter truck coefficients ($m_u$, $m_s$, $k_t$, $k_s$ and $c_s$ ) and compute the constants k1, k2, u and c or enter the constants directly in the text boxes. Click on Determine Transfer Fn button to determine the transfer function for a quarter truck model. The quarter truck transfer function is plotted as shown on screen 8, in figure A10.

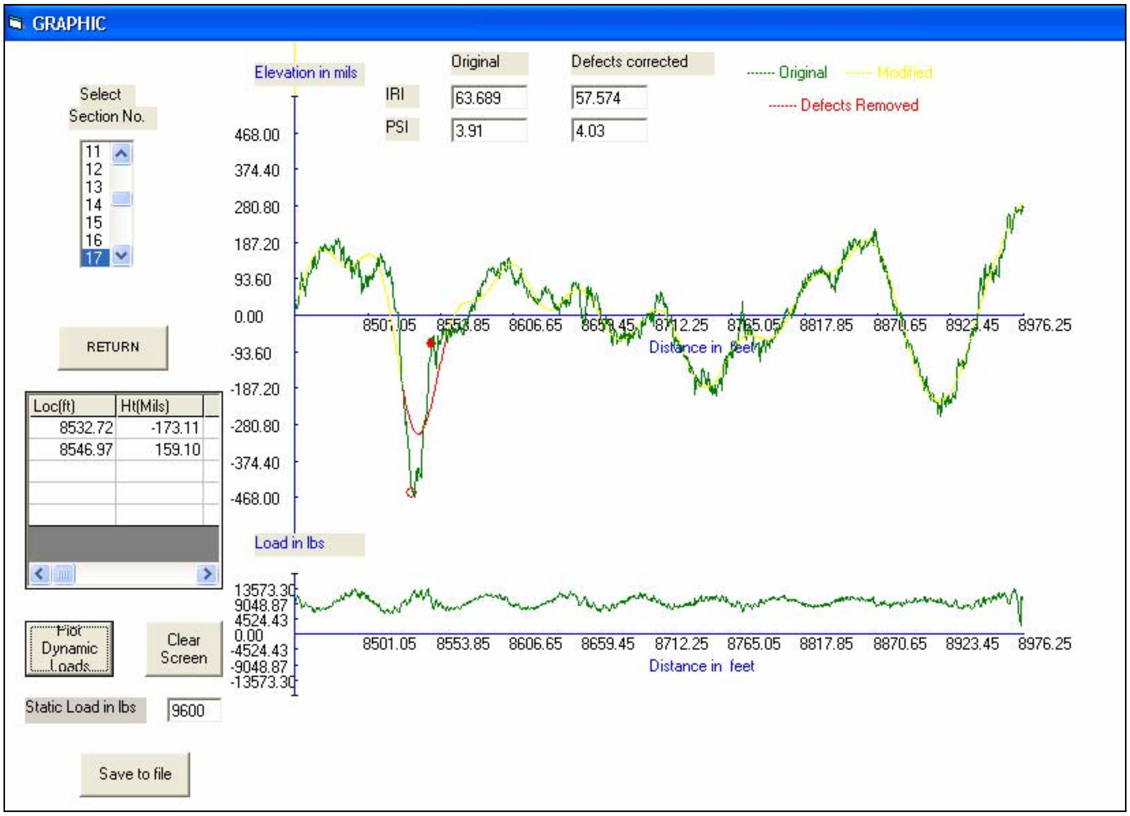



**Figure A9.** Screen 7, Graphical Plots

***b) Computing dynamic loads on pavements***

Click on Load Profile button on screen 8 to determine the dynamic loads in pavements. To view the dynamic loads on pavement click on Back button on screen 8 to open screen 2. Click on Plot button on screen 2 to open screen 7. Click on Plot Dynamic Load button on screen 7 to view the dynamic loads on pavement section. To save the dynamic loads to a text file click on Save File button on screen 7. This will open screen

6 which allows user to save dynamic loads to a chosen file. The command saves the distance in feet and the dynamic load in lbs to the chosen file.

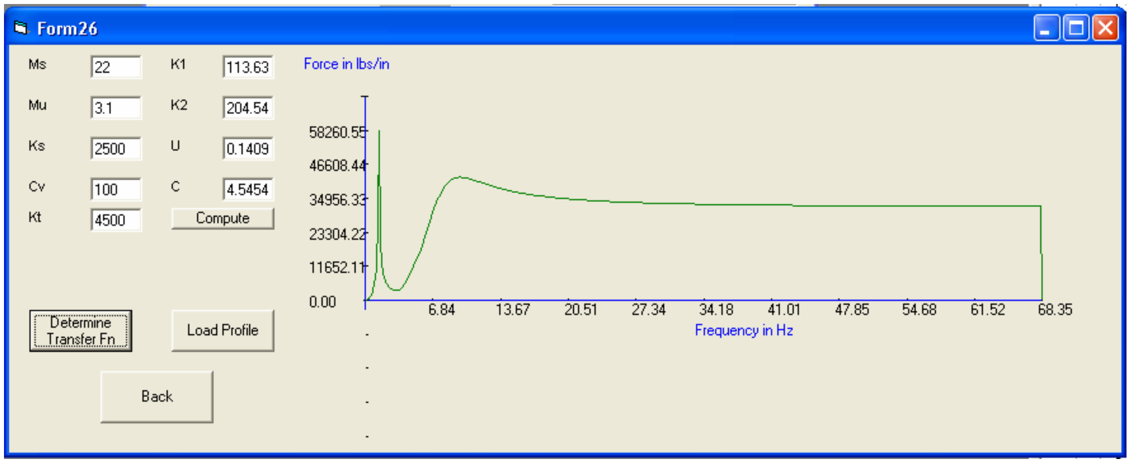



**Figure A10.** Screen 8, Dynamic load analysis.

# APPENDIX B

## Analysis of In-Service Pavement Profile Data.

**Analysis of 0.1 mile sections**

Details of defects detected on twenty 0.1 mile sections are given in Table B1. Each of the section is given a section name. The first 8 sections consist of data collected on the k2 lane of US 290 near Brenham, Texas. The next 6 sections consists of data collected on the k7 lane of SH 137 near the town of Welch, Texas, and the remaining sections consist of data collected on k1 lane of SH 137. The number in the section name represents the 0.1 mile section. The table gives the information on number of defects in each 0.1 mile section, the location of the defect in feet, the height of the defect in mils and the type of defect (Bump or Dip). Figures B1 to B18 show comparisons between defect locations detected by this methodology and Ride Quality 585, for each of these 18 sections.

**Table B1.** Comparison of defects detected using PAS and Ride Quality 585

| Section No. | Section Name | Details of defects detected using this methodology | | | | Details of defects detected using Ride Quality 585 | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | No. of bumps | Location in feet | Height in mils | Type of defect | No. of bumps | Location in feet | Height in mils | Type of defect |
| 1 | U290(w)k 2-17LWP | 2 | 345.79 | 167 | Bump | 2 | 345.8 | 170 | Bump |
| | | | 471.96 | -162 | Dip | | 472 | -160 | Dip |
| | | | | | | | | | |
| 2 | U290(w)k 2-17RWP | 1 | 462.46 | 172 | Bump | 1 | 465.1 | 150 | Bump |
| | | | | | | | | | |
| 3 | U290(w)k 2-7LWP | 1 | 105.06 | 151 | Bump | 1 | 105.1 | 170 | Bump |
| | | | | | | | | | |
| 4 | U290(w)k 2-7RWP | 2 | 44.87 | 167 | Bump | 2 | 41.2 | 160 | Bump |
| | | | 104.53 | 158 | Bump | 3* | 44.9* | 210 | Bump |
| | | | | | | | 104.5 | 160 | Bump |
| | | | | | | | | | |
| 5 | U290(w)k 2-24LWP | 5 | 5.28 | -285 | Dip | 3 | 339.5 | -180 | Dip |
| | | | 337.87 | -152 | Dip | 4* | 342.6* | 160 | Bump |
| | | | 389.60 | -152 | Dip | | 361.1 | 160 | Bump |
| | | | 516.83 | 152 | Bump | | 527.9 | 200 | Bump |
| | | | 522.11 | 260 | Bump | | | | |
| | | | | | | | | | |
| 6 | U290(w)k 2-24RWP | 5 | 5.28 | -186 | Dip | 4 | 31.7 | -150 | Dip |
| | | | 70.21 | 155 | Bump | 5* | 337.3 | -150 | Dip |
| | | | 337.87 | -162 | Dip | | 338.4* | -200 | Dip |
| | | | 343.15 | 225 | Bump | | 342.4 | 260 | Bump |
| | | | 521.05 | 162 | Bump | | 527.9 | 180 | Bump |
| | | | | | | | | | |
| 7 | U290(w)k 2-25LWP | 2 | 233.34 | -348 | Dip | 2 | 232.8 | -400 | Dip |
| | | | 246.54 | 151 | Bump | | 246 | 200 | Bump |

Table B1 continued

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 8 | U290(w)k 2-25RWP | 3 | 214.86 | 151 | Bump | 3 | 228.1 | -180 | Dip |
| | | | 232.81 | -239 | Dip | | 232.8 | -490 | Dip |
| | | | 248.12 | 150 | Bump | | 249.7 | 170 | Bump |
| | | | | | | | | | |
| 9 | 1045RWP 8 | 4 | 441.9 | 177 | Bump | 3 | 441.9 | 190 | Bump |
| | | | 447.2 | -157 | Dip | 4* | 446.2 | -210 | Dip |
| | | | 491.3 | 157 | Bump | | 491.3 | 160 | Bump |
| | | | 496.6 | -171 | Dip | | 495.6 | -240 | Dip |
| | | | | | | | | | |
| | | | | | | | | | |
| 10 | 1045LWP 8 | 1 | 388.28 | 188 | Bump | 1 | 388.3 | 200 | Bump |
| | | | | | | | | | |
| 11 | 1045RWP 5 | 4 | 130.67 | -164 | Dip | 4 | 69.1 | -150 | Dip |
| | | | 241.68 | -156 | Dip | 5* | 130.7 | -180 | Dip |
| | | | 254.43 | 152 | Bump | | 241.7 | -180 | Dip |
| | | | 280.99 | 150 | Bump | | 252.3 | 150 | Bump |
| | | | | | | | 254.4* | 160 | Bump |
| | | | | | | | | | |
| 12 | 1045LWP 5 | 0 | | | | 0 | | | |
| | | | | | | | | | |
| 13 | 1045RWP 7 | 3 | 397.31 | 187 | Bump | 2 | 395.7 | 250 | Bump |
| | | | 404.75 | -171 | Dip | | 404.2 | -220 | Dip |
| | | | 410.06 | -156 | Dip | | | | |
| | | | | | | | | | |
| 14 | 1045LWP 7 | 3 | 204.50 | 157 | Bump | 2 | 204.5 | 190 | Bump |
| | | | 399.44 | 154 | Bump | | 399.4 | 170 | Bump |
| | | | 405.81 | -154 | Dip | | | | |
| | | | | | | | | | |
| 15 | 1035RWP 6 | 2 | 470.08 | 171 | Bump | 2 | 470.1 | 210 | Bump |
| | | | 480.17 | -158 | Dip | | 480.7 | -180 | Dip |
| | | | | | | ** | 528 | 0 | Dip |
| | | | | | | | | | |
| 16 | 1035LWP 6 | 2 | 76.49 | -168 | Dip | 1 | 73.8 | -190 | Dip |
| | | | 87.64 | 163 | Bump | | | | |
| | | | | | | | | | |
| 17 | 1035RWP 8 | 2 | 467.9 | -152 | Dip | 2 | 445.6 | -165 | Dip |
| | | | 476.9 | 160 | Bump | | 475.4 | 250 | Bump |
| | | | | | | | | | |
| 18 | 1035LWP 8 | 0 | | | | 0 | | | |
| | | | | | | | | | |
| 19 | 1035RWP 5 | 5 | 10.62 | -157 | Dip | 5 | 20.7 | 350 | Bump |
| | | | 21.78 | 175 | Bump | 7* | 248.6 | -170 | Dip |
| | | | 246.46 | -158 | Dip | | 250.7* | -150 | Dip |
| | | | 310.20 | 187 | Bump | | 310.2 | 190 | Bump |
| | | | 449.37 | -157 | Dip | | 320.3 | -150 | Dip |
| | | | | | | | 321.9* | -160 | Dip |
| | | | | | | | 449.4 | -160 | Dip |

Table B1 continued

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 20 | 1035LWP 5 | 7 | 20.18 | 153. | Bump | 6 | 20.2 | 190 | Bump |
| | | | 33.99 | -229 | Dip | 8* | 33.5 | -180 | Dip |
| | | | 39.31 | -237 | Dip | | 35.6* | -210 | Dip |
| | | | 253.90 | 173 | Bump | | 253.4 | 170 | Bump |
| | | | 303.30 | 162 | Bump | | 256.6* | 160 | Bump |
| | | | 315.51 | -151 | Dip | | 304.9 | 170 | Bump |
| | | | 376,07 | -174 | Dip | | 315 | 150 | Dip |
| | | | | | | | 375 | 160 | Dip |

* Defects are spaced less than 5 feet. Defects spaced within 5 feet of one another are treated as single defect.
** A bump at 528 feet with out height is detected by Ride Quality -585

Following table gives the details of IRI of the original and modified profile and the cutoff frequencies used for generating modified profile for each of these 20 sections.

**Table B2.** IRI for 0.1 mile profile sections

| Section No. | Section Name | IRI of original profile | IRI of modified profile | Cutoff Frequency in cycles/inch |
|---|---|---|---|---|
| 1 | U290(w)k2-17LWP | 66 | 14.1 | 0.001892346 |
| 2 | U290(w)k2-17RWP | 77.3 | 12.2 | 0.001261564 |
| 3 | U290(w)k2-7LWP | 65.3 | 34.9 | 0.001892346 |
| 4 | U290(w)k2-7RWP | 75.7 | 26.9 | 0.002365432 |
| 5 | U290(w)k2-24LWP | 74.4 | 43.3 | 0.001575381 |
| 6 | U290(w)k2-24RWP | 79.8 | 35.4 | 0.001890457 |
| 7 | U290(w)k2-25LWP | 102.5 | 64.2 | 0.002052092 |
| 8 | U290(w)k2-25RWP | 105 | 74 | 0.002052092 |
| 9 | 1045RWP8 | 98.4 | 30.6 | 0.00220746 |
| 10 | 1045LWP8 | 66.7 | 25.3 | 0.002365136 |
| 11 | 1045RWP5 | 97 | 38.4 | 0.002365136 |
| 12 | 1045LWP5* | 60.3 | 31.4 | 0.002365136 |
| 13 | 1045RWP7 | 86.6 | 45.6 | 0.002365136 |
| 14 | 1045LWP7 | 67.8 | 32.6 | 0.001892109 |
| 15 | 1035RWP6 | 96.3 | 46.9 | 0.002365136 |

Table B2 Continued

| | | | | |
|---|---|---|---|---|
| 16 | 1035LWP6 | 72.2 | 37.7 | 0.001892109 |
| 17 | 1035RWP8 | 92.6 | 54.3 | 0.002365136 |
| 18 | 1035LWP8* | 61.4 | 30.9 | 0.002365136 |
| 19 | 1035RWP5 | 111.6 | 56 | 0.002049785 |
| 20 | 1035LWP5 | 90.2 | | 0.001576757 |

* Sections with no defects.

After obtaining range of frequencies that best compare with defects detected by Ride Quality -585, an analysis was carried out to determine a default frequency that may be used in absence of user specified frequency. Frequency of 0.0019 cycles/in showed good comparison to defects obtained by Ride Quality -585 and PAS (at different frequencies). The details of defects thus obtained are tabulated in Table B3.

**Table B3.** Defects detected at cutoff frequency of 0.0019 cycles/in

| Section No. | Section Name | Details of defects detected at cutoff frequency of 0.0019 cycles/in | | | |
|---|---|---|---|---|---|
| | | No. of bumps | Location in feet | Height in mils | Type of defect |
| 1 | U290(w)k2-17LWP | 2 | 345.79 | 163 | Bump |
| | | | 471.9 | -183 | Dip |
| | | | | | |
| 2 | U290(w)k2-17RWP | 0 | | | |
| | | | | | |
| 3 | U290(w)k2-7LWP | 0 | | | |
| | | | | | |
| 4 | U290(w)k2-7RWP | 2 | 41.18 | 159 | Bump |
| | | | 46.46 | 161 | Bump |
| | | | | | |
| 5 | U290(w)k2-24LWP | 3 | 5.28 | -231 | |
| | | | 339.98 | -158 | |
| | | | 520.5 | 152 | |
| | | | | | |
| 6 | U290(w)k2-24RWP | 5 | 5.28 | -173 | Dip |
| | | | 70.24 | 152 | Bump |
| | | | 338.3 | -173 | Dip |

Table B3 continued

| | | | | | |
|---|---|---|---|---|---|
| | | | 343.6 | 203 | Bump |
| | | | 523.1 | 152 | Bump |
| | | | | | |
| 7 | U290(w)k2-25LWP | 2 | 233.34 | -348 | Dip |
| | | | 246.54 | 151 | Bump |
| | | | | | |
| 8 | U290(w)k2-25RWP | 3 | 214.86 | 151 | Bump |
| | | | 232.81 | -239 | Dip |
| | | | 248.12 | 150 | Bump |
| | | | | | |
| 9 | 1045RWP8 | 3 | 441.9 | 184 | Bump |
| | | | 447.2 | -163 | Dip |
| | | | 495.5 | -154 | Dip |
| | | | | | |
| 10 | 1045LWP8 | 1 | 388.2 | 192.3 | Bump |
| | | | | | |
| 11 | 1045RWP5 | 5 | 69.05 | -150 | Dip |
| | | | 130.6 | -161 | Dip |
| | | | 241.6 | -171 | Dip |
| | | | 254.4 | 164 | Bump |
| | | | 301.7 | 162 | Bump |
| | | | | | |
| 12 | 1045LWP5 | 0 | | | |
| | | | | | |
| 13 | 1045RWP7 | 3 | 397.3 | 187 | Bump |
| | | | 404.7 | -160 | Dip |
| | | | 410 | -152 | Dip |
| | | | | | |
| 14 | 1045LWP7 | 2 | 205.56 | 154 | Bump |
| | | | 399.4 | 169 | Bump |
| | | | | | |
| 15 | 1035RWP6 | 4 | 469.5 | 154 | Bump |
| | | | 479.5 | -158 | Dip |
| | | | 484.9 | -200 | Dip |
| | | | 521 | -152 | Dip |
| | | | | | |
| 16 | 1035LWP6 | 2 | 76.4 | -162 | Dip |
| | | | 86.5 | 161 | Bump |
| | | | | | |
| 17 | 1035RWP8 | 2 | 467.4 | -173 | Dip |
| | | | 476.9 | 165 | Bump |

Table B3 continued

| | | | | | |
|---|---|---|---|---|---|
| 18 | 1035LWP8 | 0 | | | |
| | | | | | |
| 19 | 1035RWP5 | 5 | 10.6 | -157 | Dip |
| | | | 21.7 | 175 | Bump |
| | | | 246.4 | -158 | Dip |
| | | | 310.2 | 187 | Bump |
| | | | 449.3 | -157 | Dip |
| | | | | | |
| 20 | 1035LWP5 | 4 | 20.72 | 153 | Bump |
| | | | 33.9 | -189 | Dip |
| | | | 39.3 | -191 | Dip |
| | | | 305.42 | 166 | Bump |

Figures B1 to B18 show graphical comparisons of defects detected using PAS and Ride QC 585 for each of the eighteen 0.1 mile sections (section no 12 and 18 do not have any defects). The series PAS shows defect locations identified by using cutoff frequency shown in Table B2. Series Ride Quality 585 represents the defects detected by TxDOT's Ride Quality 585 software whereas series 0.0019 shows defect locations identified by PAS using a cutoff frequency of 0.0019 cycles/in.

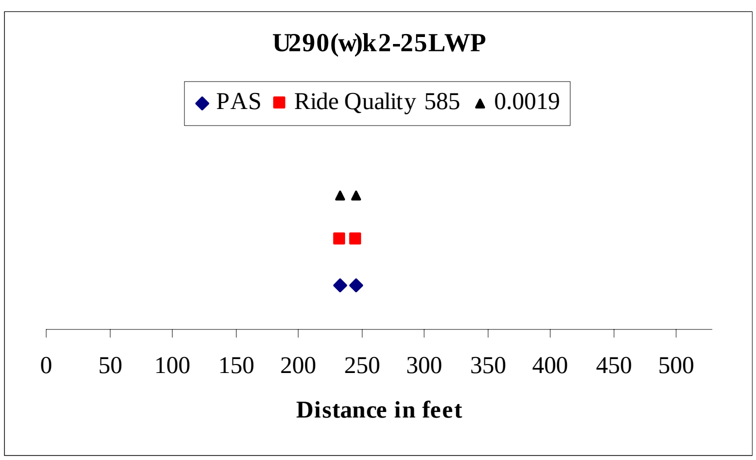



**Figure B1.** Comparison of defects for U290(w)k2-17LWP

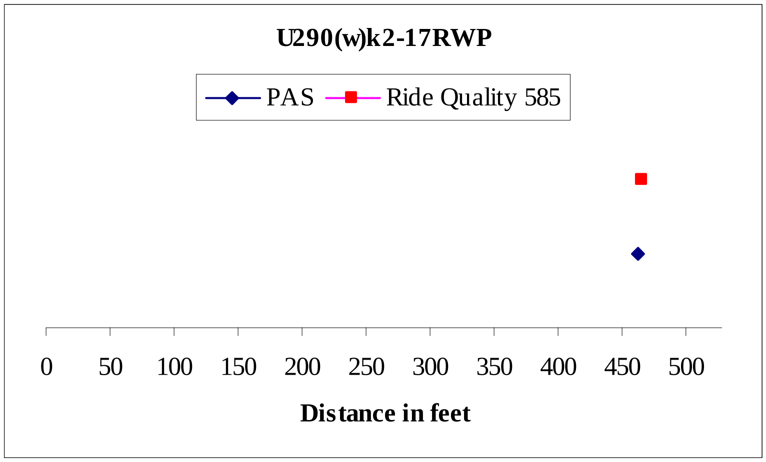



**Figure B2.** Comparison of defects for U290(w)k2-17RWP

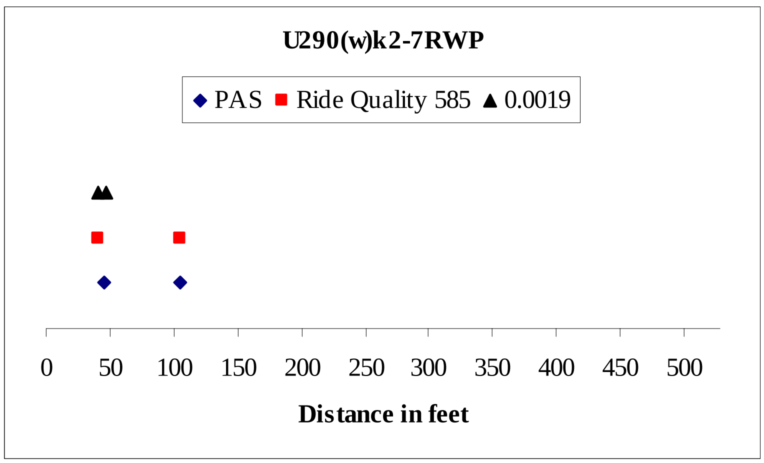



**Figure B3.** Comparison of defects for U290(w)k2-7RWP

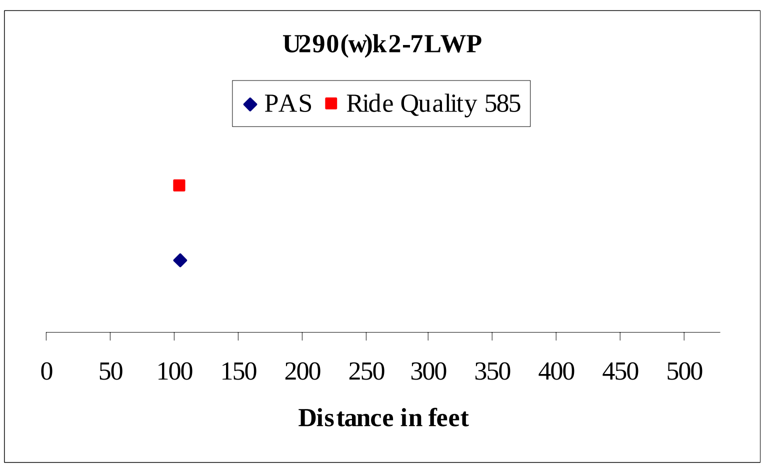



**Figure B4.** Comparison of defects for U290(w)k2-7LWP

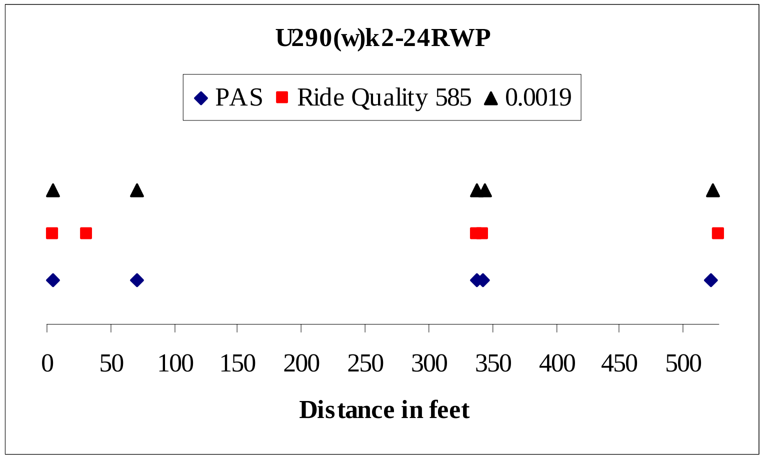



**Figure B5.** Comparison of defects for U290(w)k2-24RWP

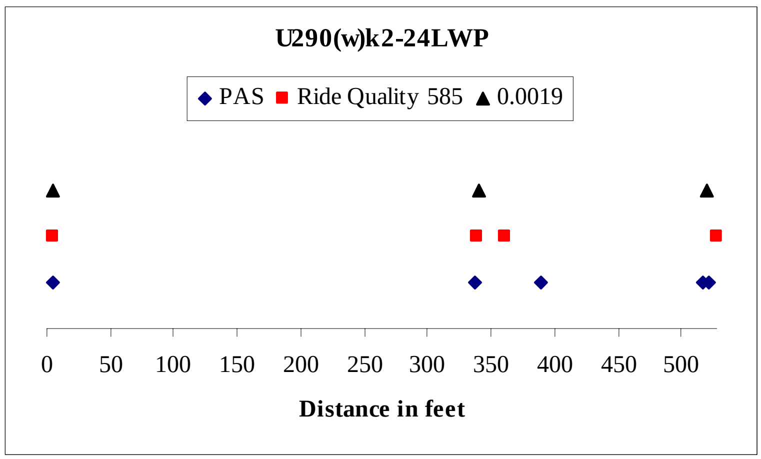



**Figure B6**. Comparison of defects for U290(w)k2-24LWP

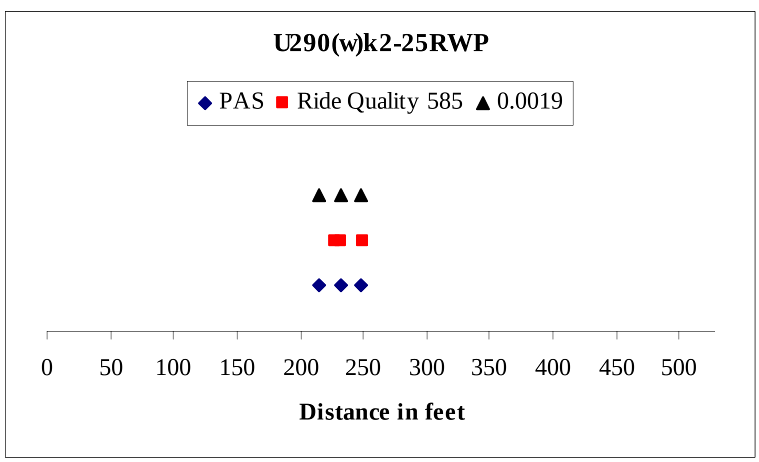



**Figure B7.** Comparison of defects for U290(w)k2-25RWP

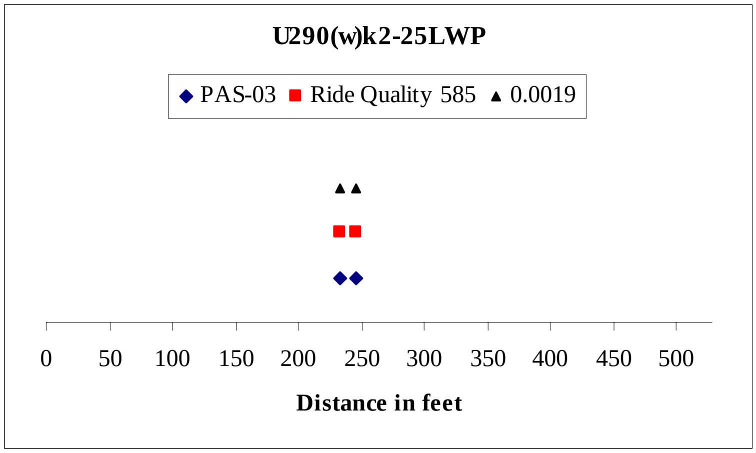



**Figure B8.** Comparison of defects for U290(w)k2-25LWP

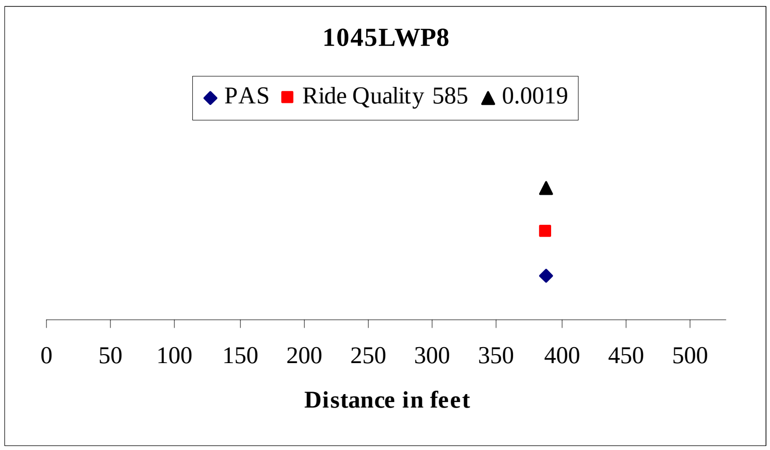



**Figure B9.** Comparison of defects for 1045LWP8

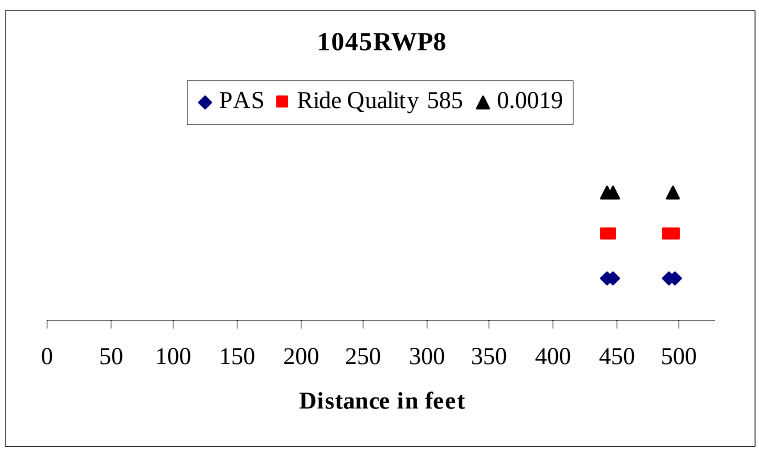



**Figure B10.** Comparison of defects for 1045RWP8

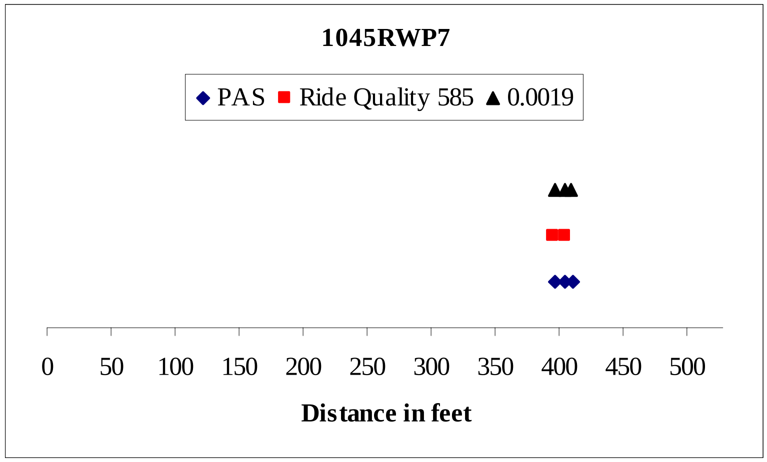



**Figure B11.** Comparison of defects for 1045RWP7

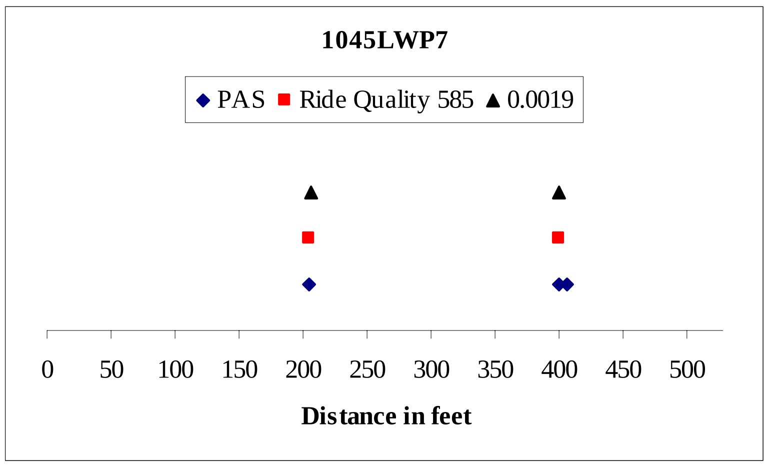



**Figure B12.** Comparison of defects for 1045LWP7

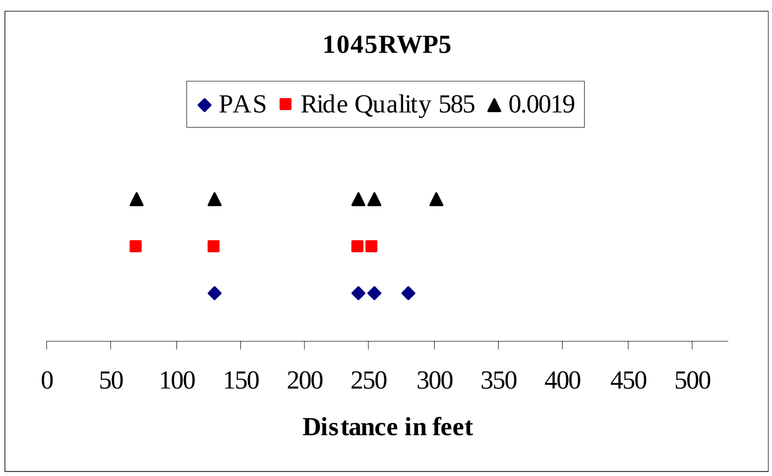



**Figure B13.** Comparison of defects for 1045RWP5

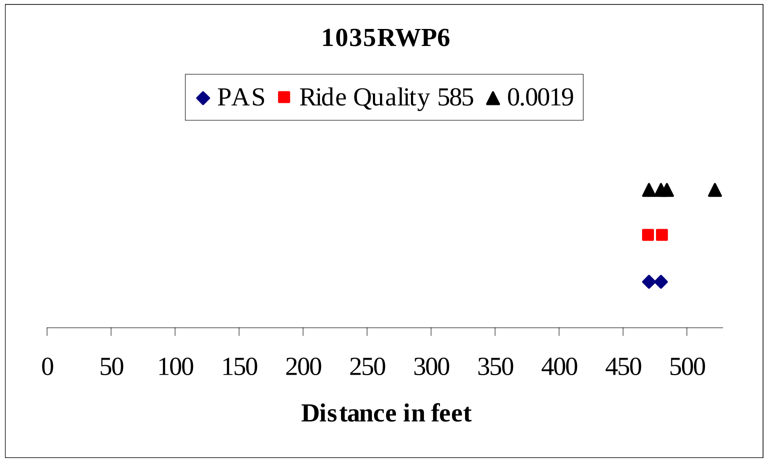



**Figure B14.** Comparison of defects for 1035RWP6

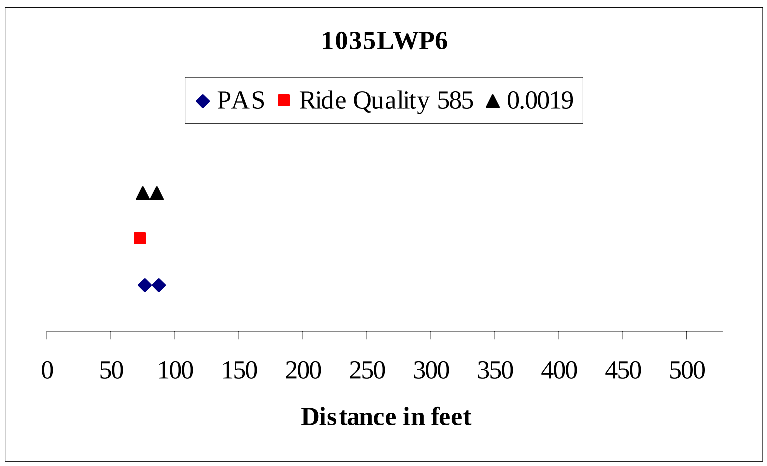



**Figure B15.** Comparison of defects for 1035LWP6

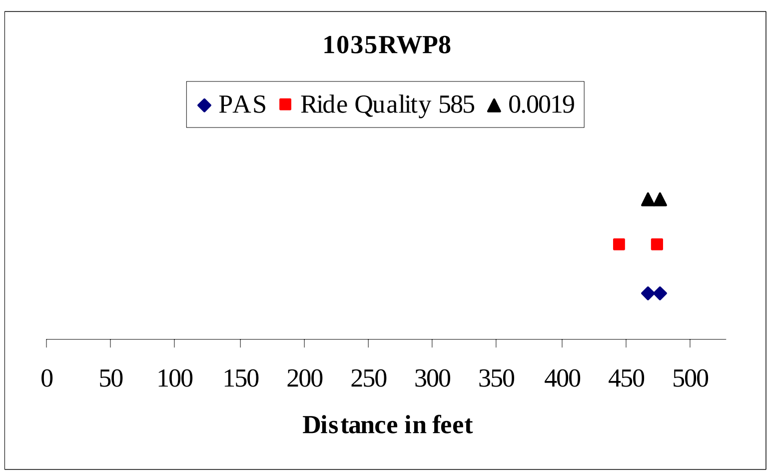



**Figure B16.** Comparison of defects for 1035RWP8

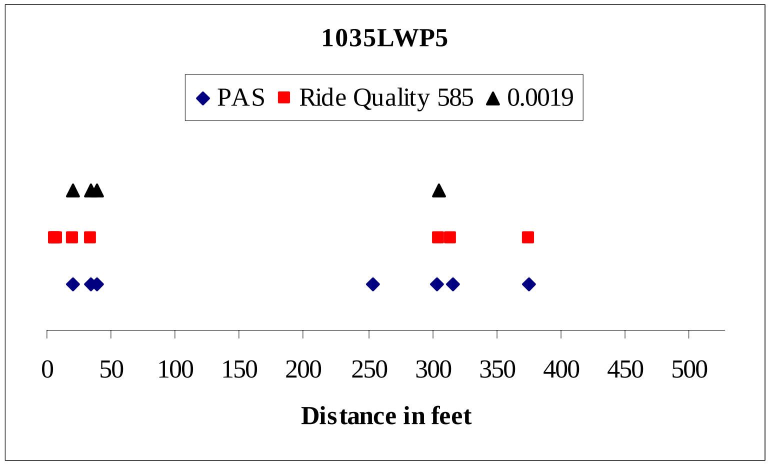



**Figure B17.** Comparison of defects for 1035LWP5

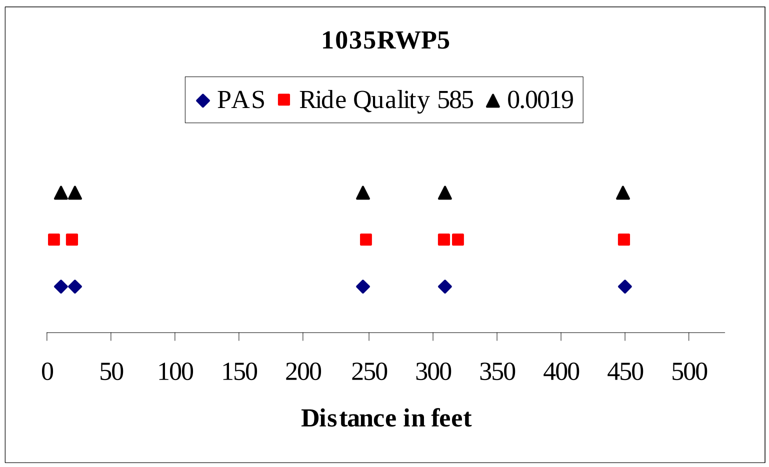



**Figure B18.** Comparison of defects for 1035RWP5

**Analysis of 3 mile sections.**

Four lanes of more than 3 miles in length were analyzed to determine the defect locations and change in roughness that may be achieved on removal of the defects. Table B3 gives the details of only those 0.1-mile sections, in each of the four lanes (K1, K2, K6 and K7) on US 290 near Brenham, Texas, where defects were identified.

**Table B4.** Details of defects detected on 3 mile sections

| Sec Name | Defect location in ft | Height of defect in mils | Beginning of defect location in ft | End of defect location in ft | Type | IRI of Original profile | PSI of Original profile | IRI of profile with defects removed | PSI of profile with defects removed |
|---|---|---|---|---|---|---|---|---|---|
| **K1** | | | | | | | | | |
| k1-1.7 | 8532 | -173 | 8526 | 8541 | Dip | 63.68 | 3.91 | 57.57 | 4.03 |
| | 8547 | 159 | 8542 | 8558 | Bump | | | | |
| k1-2.3 | 11992 | 169 | 11983 | 11997 | Bump | 71.98 | 3.76 | 68.95 | 3.79 |
| k1-2.4 | 12450 | -162 | 12443 | 12458 | Dip | 75.25 | 3.37 | 66.89 | 3.6 |
| k1-2.5 | 12874 | -234 | 12870 | 12880 | Dip | 97.25 | 3.32 | 84.56 | 3.58 |
| | 13115 | -164 | 13110 | 13119 | Dip | | | | |
| k1-2.7 | 13797 | 158 | 13788 | 13803 | Bump | 88.32 | 3.6 | 79.10 | 3.78 |
| | 13850.9 | -168 | 13847.3 | 13859.9 | Dip | | | | |
| k1-3.1 | 15884 | 153 | 15879 | 15895 | Bump | 83.97 | 3.59 | 78.77 | 3.67 |
| | 16385 | 157 | 16374 | 16399 | Bump | | | | |
| **K2** | | | | | | | | | |
| k2-0.1 | 15.3 | 154 | 2 | 31 | Bump | 65.88 | 3.72 | 60.67 | 3.82 |
| k2-0.7 | 3240 | 158 | 3235 | 3248 | Bump | 58.34 | 3.93 | 56.37 | 3.93 |
| k2-2.4 | 12453 | -158 | 12445 | 12456 | Dip | 62.81 | 3.42 | 55.74 | 3.61 |
| | 12458 | 172 | 12455 | 12464 | Bump | | | | |
| k2-2.5 | 12876 | -188 | 12869 | 12885 | Dip | 93.6 | 3.34 | 83.79 | 3.65 |
| | 12890 | 158 | 12884 | 12902 | Bump | | | | |
| k2-2.7 | 14203 | 168 | 14202 | 14204 | Bump | 84.24 | 3.73 | 83.52 | 3.73 |
| k2-2.8 | 14547 | 175 | 14546 | 14548 | BUMP | 74.50 | 3.75 | 72.06 | 3.77 |
| | 14589 | 185 | 14585 | 14596 | Bump | | | | |
| k2-2.9 | 14893 | 150 | 14889 | 14898 | Bump | 73.12 | 3.63 | 69.59 | 3.65 |
| K2-3.1 | 16191 | -161 | 16173 | 16199 | Dip | 97.54 | 3.49 | 85.54 | 3.67 |
| | 16240 | -177 | 16234 | 16248 | Dip | | | | |
| | 16324 | -159 | 16319 | 16352 | Dip | | | | |
| **K7** | | | | | | | | | |
| K7-0.1 | 3 | -159 | 0 | 18 | Dip | 125.5 | 3.06 | 88.02 | 3.56 |
| | 9 | -183 | 0 | 18 | Dip | | | | |
| | 21 | 167 | 17 | 29 | Bump | | | | |
| | 231 | 167 | 216 | 252 | Bump | | | | |
| | 239 | -172 | 216 | 252 | Dip | | | | |
| | 239 | -172 | 216 | 252 | Dip | | | | |
| | 309 | 160 | 306 | 332 | Bump | | | | |
| | 315 | 158 | 306 | 332 | Bump | | | | |
| | 321 | -169 | 306 | 332 | Dip | | | | |

Table B4 continued

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 326 | -290 | 306 | 332 | Dip | | | | |
| | 338 | 154 | 331 | 352 | Bump | | | | |
| K7-0.2 | 718 | -163 | 714 | 723 | Dip | 93.68 | 3.53 | 77.4 | 3.7 |
| | 802 | -155 | 778 | 815 | Dip | | | | |
| | 807 | -186 | 778 | 815 | Dip | | | | |
| | 819 | 162 | 814 | 835 | Bump | | | | |
| K7-0.8 | 3768 | -157 | 3761 | 3790 | Dip | 94.40 | 3.28 | 75.18 | 3.67 |
| | 3780 | 161 | 3761 | 3790 | Bump | | | | |
| | 4192 | 158 | 4187 | 4200 | Bump | | | | |
| K7-2.8 | 14712 | -152 | 14709 | 14720 | Dip | 57.30 | 3.93 | 53.87 | 4.01 |
| **K6** | | | | | | | | | |
| K6-0.1 | 38 | -168 | 33 | 45 | Dip | 95.12 | 3.57 | 91.40 | 3.62 |
| K6-0.8 | 3767 | -164 | 3758 | 3780 | Dip | 86.82 | 3.33 | 71.93 | 3.69 |
| | 3773 | 153 | 3758 | 3780 | Bump | | | | |
| | 4191 | -267 | 4181 | 4200 | Dip | | | | |

*Dynamic load criteria*

Figures B19 to B22 show defects identified by using a cutoff frequency of 0.0019 cycles/in and a cutoff frequency of 0.0025 cycles/in on lanes k1, k2, k6 and k7. This analysis was carried out to determine whether defects identified by using a cutoff frequency obtained from the quarter truck dynamic load transfer function are detected by a cutoff frequency chosen on basis of the IRI gain function. It is observed that a cutoff frequency of 0.0019 cycles/in takes into account the defects identified using dynamic load transfer function.

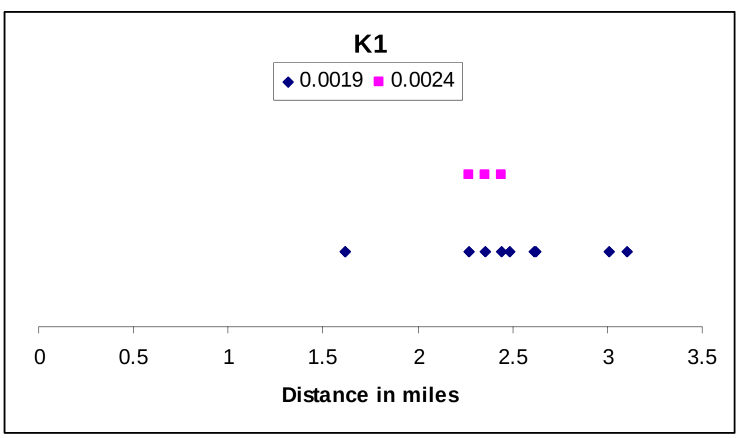



**Figure B19.** Comparison of defects detected on K1

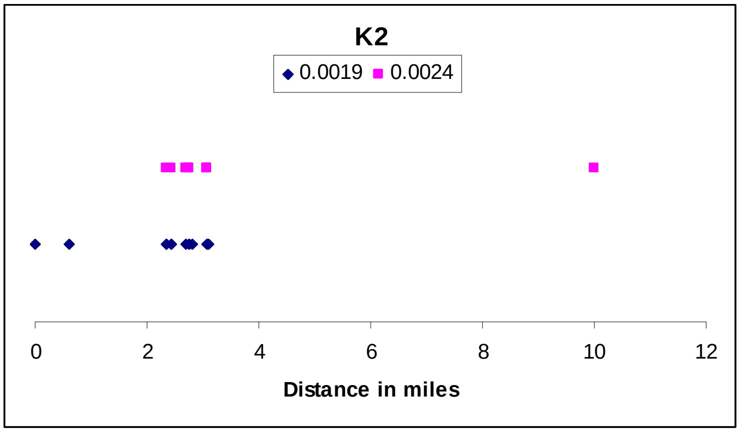



**Figure B20.** Comparison of defects detected on K2

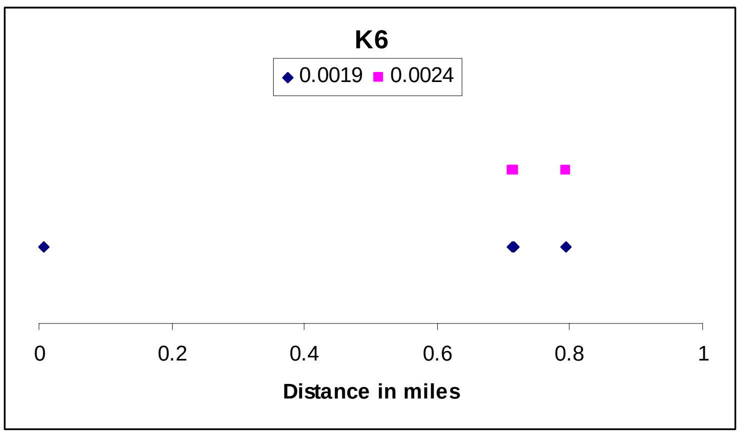



**Figure B21.** Comparison of defects detected on K6

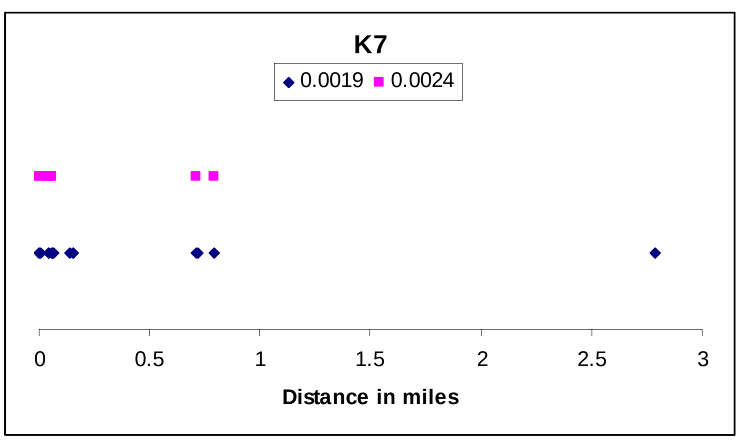



**Figure B22.** Comparison of defects detected on K7

Illustration of the procedure to identify critical defects was given in Chapter IV. Figure B23 shows the 0.1 mile profile plot which was used. The profile plot shows original and modified profile and the 3 defect locations identified using the methodology presented in this thesis.

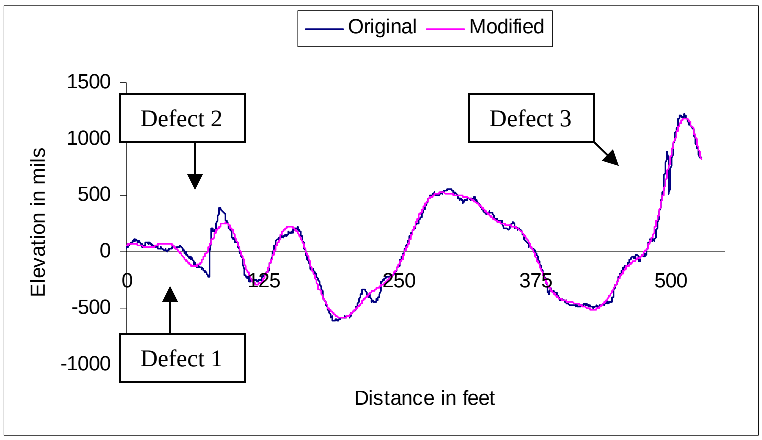



**Figure B23.** Section used to illustrate critical defect identification

# APPENDIX C
# Visual Basic code for PAS

This section consists of program code for PAS software in Visual Basic 6.0. The code is separately presented for each of the forms used in the program. The code is arranged as per screen names in Appendix A, for easy referral. Following are the support files needed to run the program.

Executable files

- Pas.exe, ShubIRI.exe,Psi.exe

DLL files

- ASYCFILT.DLL, COMCAT.DLL, DAO360.DLL, EXPSRV.DLL,MSJET40.DLL,MSJINT40.DLL,MSJTER40.DLL, MSJTES40.DLL, MSRD2X40.DLL, MSRD3X40.DLL, MSREPL40.DLL, MSSTDFMT.DLL,MSVBVM60.DLL, MSWDAT10.DLL, MSWSTR10.DLL, OLEAUT32.DL, OLEPRO32.DLL, VB5DB.DLL,VB6STKIT.DLL, VBAJET32.DLL

OCX files

- MSCHRT20.OCX, SFLXGRD.OCX, CCLP32.OCX, MDLG32.OCX

Text Files

- Output.txt ( is a input file to determine IRI), Outfile.txt (output file containing IRI value in in/mi), PSIin.txt ( input file to determine PSI), PSIout.txt(output file containing PSI value on a scale of 0-5)

Visual Basic Source files

- Profile1flex.vbp, Profile1flex.vbp, Profile1Flex.frm, startform.frm, profile plot.frm, form 26.frm, DFT.frm, Select input file.frm and form 18.frm.

**Code for Start form.frm (Screen 1)**

( Loads Screen 1, no input files needed )

```
Private Sub Command1_Click()
Load Form1
Form1.Show
Form9.Hide
End Sub
```

## CODE for Profile1Flex.frm (Screen 2)

(Generates modified profile, computes IRI and PSI for each 0.1 mile section, computes defect location and other details, computes IRI and PSI for 0.1 mile sections with defects removed. Needs input file of profile data. Uses Output.txt, Outfile.txt, PSIin.txt and PSIout.txt at runtime)

```
Private Sub Command10_Click()
Load Form25
Form25.Show
Form25.Refresh
Dim m, z, NoSec, NoSec1 As Integer, NoSec2, NoSec3, Set1, newIRI
NoSec1 = Val(Form1.Text3.Text)
NoSec2 = Val(Form1.Text3.Text)
NoSec3 = NoSec2 / NoSec1
If NoSec3 > 1 Then
LlastSec = (NoSec2 - NoSec1) * 528
Set1 = 1
ToNoSec = NoSec1 + 1
ElseIf NoSec3 < 1 Then
LlastSec = (1 - (NoSec1 - NoSec2)) * 528
Set1 = 2
ToNoSec = NoSec1
End If
' Set current directory to App.path
ChDir App.Path
For z = 1 To ToNoSec
If z = ToNoSec Then
NoPoint528 = (LlastSec * 12 / SamInt)
ELStart = (z - 1) * (528 * 12 / SamInt)
ELEnd = ELStart + NoPoint528
End If
NoPoint528 = (528 * 12 / SamInt)
ELStart = (z - 1) * NoPoint528
ELEnd = z * NoPoint528
If z = ToNoSec Then
NoPoint528 = (LlastSec * 12 / SamInt)
ELStart = (z - 1) * (528 * 12 / SamInt)
ELEnd = ELStart + NoPoint528
End If
Open App.Path & "\Outfile.txt" For Output As #9
Print #9, z
Close #9
newIRI = z
'calculate IRI
Open App.Path & "\Output.txt" For Output As #21 ' For IRI code use
On Error Resume Next
 ' to print the initial header for IRI input
Print #21, (ELEnd - ELStart)
Print #21, "mil"
Print #21, SamInt
Print #21, "i"
Dim j, Inp, ProfileIRI, Shub
'-------------------------
For j = ELStart To ELEnd
 Print #21, Format(TOTALBUMP1(j), "#########.00")
```

```
Next j
Close #21
Shell ("ShubIRI.exe") ' calling fortran program
Do While z = newIRI
Open App.Path & "\Outfile.txt" For Input As #4
Input #4, newIRI
Close #4
DoEvents
Loop
Inp = FreeFile()
Open App.Path & "\Outfile.txt" For Input As #Inp
Input #Inp, ProfileIRI
Close #Inp
BIRI(z) = ProfileIRI
Next z
Open App.Path & "\PSIout.txt" For Output As #19
Print #19, Shub
Close #19
Dim newPSI As String
newPSI = Shub
Open App.Path & "\PSIin.txt" For Output As #211 ' For IRI code use
Print #211, l2
Print #211, l3
Print #211, l4, 0.1, "mi"
Print #211, l5
Print #211, l6
Dim PsiPro(200000) As Integer
For j = 0 To TotalPSI - 1
PsiPro(j) = TOTALBUMP1(j)
Write #211, PsiPro(j), PsiPro(j), 0 '"##########"); Format(OrPro(j), "##########"); 0
Next j
Close #211
Dim lp As String
 Shell ("psi.exe") ' calling C program
Unload Form25
End Sub
Private Sub Command13_Click()
'"' to get BPSI
Dim lp As String, Inp, i
Inp = FreeFile()
Open App.Path & "\PSIout.txt" For Input As #Inp
Line Input #Inp, lp
Line Input #Inp, lp
Line Input #Inp, lp
Line Input #Inp, lp
Line Input #Inp, lp
Line Input #Inp, lp
Line Input #Inp, lp
i = 1
Do Until EOF(Inp)
Input #Inp, BPSI(i)
i = i + 1
Loop
Close #Inp
Dim Rsp As String
' show save as dialog box
```

```
CommonDialog1.ShowSave
' check if file exists,if it does confirm overwrite
If Dir(CommonDialog1.FileName) <> "" Then
Rsp = MsgBox("Overwrite File?", vbYesNoCancel, "File Exists")
If Rsp <> vbYes Then Exit Sub
End If
' open filename for output, use append to add to a file
Open CommonDialog1.FileName For Output As #1
Print #1, "*****"; SelectedFile; "*****"
Print #1, ""
Print #1, " File Name:"; CommonDialog1.FileName
Print #1, "Header Information"
Print #1, l2
Print #1, l3
Print #1, l4
Print #1, l5
Print #1, l6
Print #1, "Defect Details are as follows"
Dim TYPEB, ELBUMPLOCMILES
Print #1, "Defect no.  Location      Location      Height      Beginning       End          TYPE "
Print #1, "           in miles       in feet       in mils       Location     Location              "
Print #1, " "
For K = 1 To NoBumbsform2
If ELBUMPHT(K) < 0 Then
TYPEB = "DIP"
ElseIf ELBUMPHT(K) > 0 Then
TYPEB = "BUMP"
End If
ELBUMPLOCMILES = (ELBUMPLOC(K) / 5280)
Print #1, K, Format(ELBUMPLOCMILES, "###0.000"), Format(ELBUMPLOC(K), "#####0"), Format(ELBUMPHT(K), "###0"), Format(ELBUMPBIGNG(K), "#####0"), Format(ELBUMPEND(K), "#####0"), TYPEB
Next K
Print #1, "Total number of Defects is"; K - 1
Print #1, ""
Print #1, "  Section             Original                 Defects removed"
Print #1, "    No.       IRI           PSI           IRI            PSI  "
Print #1, ""
For K = 1 To Val(Form1.Text3.Text)
Print #1, K * 0.1, PIRI(K), PPSI(K), BIRI(K), BPSI(K)
Next K
'Print #1, Val(Form1.Text4.Text)
Close #1
End Sub
Private Sub Command11_Click()
Load Form26
Form26.Show
End Sub
Private Sub Command12_Click()
Load Form25
Form25.Show
Form25.Refresh
Const PI = 3.14159265
Dim m, Offset21, leadin As Integer, leadout As Integer, n1 As Integer
n = (Dist * 12) / SamInt
leadin = Val(Form3.Text2.Text) * 12 / SamInt
```

```
leadout = Val(Form3.Text3.Text) * 12 / SamInt
ReDim RL2(n / 2), IM2(n / 2), FR2(n / 2)
n1 = n - leadin - leadout
Dim k1
k1 = 0
For K = leadin To n - leadout
OrPro1(k1) = OrPro(K)
k1 = k1 + 1
Next K
For m = 0 To n / 2
RL = 0
IM = 0
RL1 = 0
IM1 = 0
k1 = 0
For K = 0 To n
RL = OrPro(K) * Cos(2 * PI * m * k1 / n)
IM = OrPro(K) * Sin(2 * PI * m * k1 / n)
RL1 = RL1 + RL
IM1 = IM1 + IM
k1 = k1 + 1
Next K
If m = 0 Then
RL2(m) = RL1 / n
IM2(m) = IM1 / n
FR2(m) = m / (SamInt * n)
Offset21 = RL2(m)
Else
RL2(m) = 2 * RL1 / n
IM2(m) = 2 * IM1 / n
FR2(m) = m / (SamInt * n)
End If
If FR2(m) > Val(Text4.Text) Then
Exit For
End If
Next m
NoFreq1 = m ' to be used with cos and sine commond on form 1
noofpoints = m  ' to be used in bump form and also for modifyinput in form 1(profile form
'MSFlexGrid1.Rows = m + 50
'%%%%%%%%%%%%%%%%%%%%DFT
Dim Freq(), RA(), IA(), NSam
Dim XK As Single, XK1 As Single
Dim i%, j1 As Long
Interval = Val(Text2.Text)
 m1 = m
 m123 = m

ReDim Freq(m), RA(m), IA(m)

For i = 0 To m - 1 ' getting DFT input
Freq(i) = FR2(i)
RA(i) = RL2(i)
IA(i) = IM2(i)
Next i
' Calculating Profile
B = 0
```

```
For j1 = 0 To n
XK1 = 0
XK = 0
For i = 0 To m - 1
XK = RA(i) * Cos(2 * PI * i * j1 / n) + IA(i) * Sin(2 * PI * i * j1 / n)
XK1 = XK1 + XK
Next i
TOTAL(j1) = XK1
Next j1
K = 0
For j1 = 0 To n
FINALTOTAL(j1) = TOTAL(K)
K = K + 1
Next j1
k1 = 0
For K = leadin To n - leadout
FINALTOTAL1(k1) = FINALTOTAL(K)
k1 = k1 + 1
Next K
Unload Form25
End Sub
Private Sub Command2_Click()
Load Form9
Form9.Show
Form1.Hide
End Sub
Private Sub Command3_Click()
NoRows = 2000
Dim BUMP(), LOCA(), NoBumps, LOCA1
ReDim BUMP(200000), LOCA(200000), Height(200000)
Dim i1 As Integer, i As Long
NoBumps = 1
TotalSamPts = Val(Text1.Text * 5280 * 12) / SamInt
For i = 0 To TotalSamPts
BUMP(i) = OrPro1(i) - FINALTOTAL1(i)
TOTALBUMP1(i) = OrPro1(i)
If BUMP(i) > 150 Then
Dim p2
p2 = 10
NoBumps = NoBumps + 1
LOCA(NoBumps) = i * SamInt / 12
Height(NoBumps) = BUMP(i)
ElseIf BUMP(i) < -150 Then
p2 = 10
NoBumps = NoBumps + 1
LOCA(NoBumps) = i * SamInt / 12
Height(NoBumps) = BUMP(i)
End If
Next i
Form18.MSFlexGrid1.Rows = 1000
TotalBumps = NoBumps
Form18.MSFlexGrid1.TextMatrix(0, 0) = "No"
Form18.MSFlexGrid1.TextMatrix(0, 1) = "Location(Miles)"
Form18.MSFlexGrid1.TextMatrix(0, 2) = "Height(Mils)"
LOCA1 = -Val(Text10.Text)
i1 = 1
```

```
If TotalBumps = 1 Then
Exit Sub
End If
For i = 2 To TotalBumps
If LOCA(i) - LOCA1 >= Val(Text10.Text) Then
Form18.MSFlexGrid1.TextMatrix(i1, 0) = i1
Form18.MSFlexGrid1.TextMatrix(i1, 1) = Format(LOCA(i) / 5280, "####0.0000")
Form18.MSFlexGrid1.TextMatrix(i1, 2) = Format(Height(i), "####0")
ELBUMPNO(i1) = LOCA(i) * 12 / SamInt
ELBUMPHT(i1) = Height(i)
ELBUMPLOC(i1) = LOCA(i)
'************ to find width***********
Dim Arryno, BeginingLoc, Arrynoneg, EndLoc, Arrynopos
Dim A2%, ABVAL, Bump21
Arryno = LOCA(i) * 12 / SamInt
Arrynoneg = 0
ABVAL = 0
Do
ABVAL = Abs(OrPro1(Arryno + Arrynoneg) - FINALTOTAL1(Arryno + Arrynoneg))
Arrynoneg = Arrynoneg - 1
If Arrynoneg = -Arryno Then ' in case bump is detected right at the begning
Exit Do
End If
Loop Until ABVAL < 10
BeginingLoc = Arryno + Arrynoneg
Arrynopos = 0
ABVAL = 0
Do
ABVAL = Abs(OrPro1(Arryno + Arrynopos) - FINALTOTAL1(Arryno + Arrynopos)) '< 2
Arrynopos = Arrynopos + 1
Loop Until ABVAL < 10
EndLoc = Arryno + Arrynopos
For A2 = BeginingLoc To EndLoc
TOTALBUMP1(A2) = FINALTOTAL1(A2)
Next A2
ELBUMPBIGNG(i1) = BeginingLoc * SamInt / 12
ELBUMPEND(i1) = EndLoc * SamInt / 12
'***********************************
LOCA1 = LOCA(i)
i1 = i1 + 1
End If
Next i
NoBumbsform2 = i1 - 1
Form18.MSFlexGrid1.Rows = i1 + 10
NoRows = i1 + 4
"" to get PSI
Dim lp As String
Inp = FreeFile()
Open App.Path & "\PSIout.txt" For Input As #Inp
Line Input #Inp, lp
Line Input #Inp, lp
Line Input #Inp, lp
Line Input #Inp, lp
Line Input #Inp, lp
Line Input #Inp, lp
Line Input #Inp, lp
```

```
i = 1
Do Until EOF(Inp)
Input #Inp, PPSI(i)
i = i + 1
Loop
Close #Inp
Load Form18
Form18.Show
'Form1.Hide
Back = 1
End Sub
Private Sub Command4_Click()
"" to get PSI
Dim lp As String, Inp, i
Inp = FreeFile()
Open App.Path & "\PSIout.txt" For Input As #Inp
Line Input #Inp, lp
Line Input #Inp, lp
Line Input #Inp, lp
Line Input #Inp, lp
Line Input #Inp, lp
Line Input #Inp, lp
Line Input #Inp, lp
i = 1
Do Until EOF(Inp)
Input #Inp, BPSI(i)
i = i + 1
Loop
Close #Inp
Form2.List1.Clear
Dim K%
For K = 1 To ToNoSec
 Form2.List1.AddItem K
Next K
Load Form2
Form2.Show
Back = 1
End Sub
Private Sub Command6_Click()
Dim Inp As Integer
Dim m, i, K, B1   'Blank
Dim RL, IM, RL1, IM1, RL2() As Single, IM2() As Single, FR2() As Single
Const PI = 3.14159265
Dim l1 As String, m1 As String ', LR As String
Dim PInp
If NoWPath = "LR" Then
Load Form3
Form3.Show
Form4.Hide
Close #PInp
'*********************************************
 ' this is extra code which is not compatible
Else
PInp = FreeFile()
Open (SelectedFile) For Input As #PInp
Line Input #PInp, l1
```

```
Line Input #PInp, l1
Input #PInp, B1, ElUnit, NoWPath, SamInt, DisUnit
Line Input #PInp, l1
Line Input #PInp, l1
i = 0
Do
Input #PInp, lp(i)
 OrPro(i) = lp(i)
i = i + 1
Loop Until EOF(PInp)
Dist = (SamInt * (i - 1))
Close #PInp
n = i
'ReDim A(N), B(N)
Open App.Path & "\Input.txt" For Output As #1
Write #1, Dist, SamInt
ReDim RL2(n / 2 + 1), IM2(n / 2 + 1), FR2(n / 2 + 1)
For m = 0 To n / 2
RL = 0
IM = 0
RL1 = 0
IM1 = 0
For K = 0 To n - 1
RL = lp(K) * Cos(2 * PI * m * K / n)
M = lp(K) * Sin(2 * PI * m * K / n)
RL1 = RL1 + RL
IM1 = IM1 + IM
Next K
If m = 0 Then
RL2(m) = RL1 / n
IM2(m) = IM1 / n
FR2(m) = m / (SamInt * n)
Else
RL2(m) = 2 * RL1 / n
IM2(m) = 2 * IM1 / n
FR2(m) = m / (SamInt * n)
End If
Write #1, FR2(m); RL2(m); IM2(m)
Next m
Write #1, "000628009"; "End"; "ID"
Close #1
'***********************************
End If
End Sub
Private Sub Command8_Click()
Load Form25
Form25.Show
Form25.Refresh
Dim m, z, NoSec, NoSec1 As Integer, NoSec2, NoSec3, Set1
NoSec1 = Val(Text3.Text)
NoSec2 = Val(Text3.Text)
NoSec3 = NoSec2 / NoSec1
If NoSec3 > 1 Then
LlastSec = (NoSec2 - NoSec1) * 528
Set1 = 1
ToNoSec = NoSec1 + 1
```

```
ElseIf NoSec3 < 1 Then
LlastSec = (1 - (NoSec1 - NoSec2)) * 528
Set1 = 2
ToNoSec = NoSec1
End If
' Set current directory to App.path
ChDir App.Path
For z = 1 To ToNoSec
If z = ToNoSec Then
NoPoint528 = (LlastSec * 12 / SamInt)
ELStart = (z - 1) * (528 * 12 / SamInt)
ELEnd = ELStart + NoPoint528
End If
NoPoint528 = (528 * 12 / SamInt)
ELStart = (z - 1) * NoPoint528
ELEnd = z * NoPoint528
If z = ToNoSec Then
NoPoint528 = (LlastSec * 12 / SamInt)
ELStart = (z - 1) * (528 * 12 / SamInt)
ELEnd = ELStart + NoPoint528
End If
Open App.Path & "\Outfile.txt" For Output As #9
Print #9, z
Close #9
 newIRI = z
'calculate IRI
Open App.Path & "\Output.txt" For Output As #21 ' For IRI code use
On Error Resume Next
 ' to print the initial header for IRI input
Print #21, (ELEnd - ELStart)
Print #21, "mil"
Print #21, SamInt
Print #21, "i"
'-------------------------
For j = ELStart To ELEnd
Print #21, Format(OrPro1(j), "##########.00")
Next j
Close #21
Shell ("ShubIRI.exe") ' calling fortran program
Do While z = newIRI
Open App.Path & "\Outfile.txt" For Input As #4
Input #4, newIRI
Close #4
DoEvents
Loop
Inp = FreeFile()
Open App.Path & "\Outfile.txt" For Input As #Inp
Input #Inp, ProfileIRI
Close #Inp
PIRI(z) = ProfileIRI
Next z
Open App.Path & "\PSIout.txt" For Output As #19
Print #19, Shub
Close #19
Dim newPSI As String
newPSI = Shub
```

```
Open App.Path & "\PSIin.txt" For Output As #211 ' For IRI code use
Print #211, l2
Print #211, l3
Print #211, l4, 0.1, "mi"
Print #211, l5
Print #211, l6
Dim PsiPro(200000) As Integer
For j = 0 To TotalPSI - 1
PsiPro(j) = OrPro1(j)
Write #211, PsiPro(j), PsiPro(j), 0 '"##########"); Format(OrPro(j), "##########"); 0
Next j
Close #211
Dim lp As String
Shell ("psi.exe") ' calling C program
Form25.Label1 = "DONE"
Unload Form25
End Sub
Private Sub Command9_Click()
Load Form4
Form4.Show
Form1.Hide
Dim m1 As String ', LR As String
End Sub
```

## CODE for Select Input file.frm (Screen 3)

( Selects input file specified by user. Needs a input file selected by user)

```
Private Sub Command1_Click()
Dim PInp
Dim Inp As Integer, SamInt1
Dim m, i, K, B1   'Blank
Dim RL, IM, RL1, IM1, RL2() As Single, IM2() As Single, FR2() As Single
Const PI = 3.14159265
 Dim m1 As String ', LR As String
'****** for generating preview************
PInp = FreeFile()
Open (SelectedFile) For Input As #PInp
Line Input #PInp, l1
Line Input #PInp, l2
Line Input #PInp, l8
Line Input #PInp, l3
Line Input #PInp, l4
Line Input #PInp, l5
Line Input #PInp, l6
Line Input #PInp, l7
Close #PInp
'********************End**********
PInp = FreeFile()
Open (SelectedFile) For Input As #PInp
Line Input #PInp, l1
Line Input #PInp, l2
Input #PInp, B12, ElUnit, NoWPath, SamInt1, DisUnit
Close #PInp
If DisUnit = m Then
SamInt = SamInt1 * 39.37 ' to convert to inches
Else
SamInt = SamInt1
End If
Load Form1
Form1.Show
Form4.Hide
End Sub
Private Sub Command3_Click()
Load Form1
Form1.Show
Form4.Hide
End Sub
Private Sub Dir1_Change()
File1.Path = Dir1.Path
End Sub
Private Sub Drive1_Change()
Dir1.Path = Drive1.Drive
End Sub
Private Sub File1_Click()
SelectedFile = File1.Path & "\" & File1.FileName
End Sub
```

## CODE for Select wheelpath.frm (Screen 4)

(Reads data from input file specified by user.  Needs a input file selected by user)

```
Private Sub Command1_Click()
Dim leadin, leadout, n1
leadin = Val(Form3.Text2.Text) * 12 / SamInt
leadout = Val(Form3.Text3.Text) * 12 / SamInt
n1 = Dist / SamInt
Dim k1
k1 = 0
For K = leadin To n1 - leadout
OrPro1(k1) = OrPro(K)
k1 = k1 + 1
Next K
Form1.Text1.Text = (Dist - (Val(Text2.Text) + Val(Text3.Text))) / 5280
Form1.Text2.Text = SamInt
Form1.Text3.Text = (Dist - (Val(Text2.Text) + Val(Text3.Text))) / 528
TotalPSI = n
'Dim Numberofsections As Integer
'Numberofsections = Dist / 528
For j = 0 To TotalSamPts
FINALTOTAL(j) = OrPro(j)
Next j
Load Form1
Form1.Show
Form3.Hide
End Sub
Private Sub Command5_Click()
Form22.Text1.Text = l1
Form22.Text2.Text = l2
Form22.Text3.Text = l8
Form22.Text4.Text = l3
Form22.Text5.Text = l4
Form22.Text6.Text = l5
Form22.Text7.Text = l6
Form22.Text8.Text = l7
Load Form22
Form22.Show
'Form4.Hide
End Sub
Private Sub Option1_Click()
Col = 3
End Sub
Private Sub Option2_Click()
Col = 2
End Sub
Private Sub Option3_Click()
Dim Inp As Integer, SamInt1
On Error GoTo AwNuts
Dim m, i, K, B4    'Blank
Dim RL, IM, RL1, IM1, RL2() As Single, IM2() As Single, FR2() As Single
Const PI = 3.14159265
Dim l11 As String, m1 As String, D1
```

```
Dim Dummy
PInp = FreeFile()
Open (SelectedFile) For Input As #PInp
Line Input #PInp, l11
Line Input #PInp, l11
Input #PInp, B4, ElUnit, NoWPath, SamInt1, DisUnit
If DisUnit = "m" Then
SamInt = SamInt1 * 39.3700787 ' to convert to inches
Else
SamInt = SamInt1
End If
Close #PInp
' to acount for addition info on line 3
Open (SelectedFile) For Input As #PInp
Line Input #PInp, l2
Line Input #PInp, l3
Line Input #PInp, l4
Line Input #PInp, l5
Line Input #PInp, l6
If DisUnit = "m" Then
SamInt = SamInt1 * 39.3700787 ' to convert to inches
Else
SamInt = SamInt1
End If
i = 0
Do
If Col = 3 Then
Input #PInp, lp(i), RP(i), CO(i)
ElseIf Col = 2 Then
Input #PInp, lp(i), RP(i)
End If
OrPro(i) = lp(i) ' For ploting original profile
i = i + 1
Loop Until EOF(PInp)
Dist = SamInt * (i - 1) / 12
Close #PInp
n = i
TotalSamPts = i
Raw = 2
AwNuts:
If Err.Number = 62 Then
Dist = SamInt * (i - 1)
Raw = 3
Exit Sub
End If
Exit Sub
If Col = 3 Then
On Error GoTo AwNut
PInp = FreeFile()
Open (SelectedFile) For Input As #PInp
Line Input #PInp, l1
Line Input #PInp, l1
Input #PInp, B4, ElUnit, NoWPath, SamInt1, DisUnit
Line Input #PInp, l1
Line Input #PInp, l1
If DisUnit = "m" Then
```

```
SamInt = SamInt1 * 39.3700787 ' to convert to inches
Else
SamInt = SamInt1
End If
i = 0
Do
Input #PInp, lp(i), RP(i), CO(i)
OrPro(i) = lp(i) ' For ploting original profile
i = i + 1
Loop Until EOF(PInp)
Dist = SamInt * (i - 1) / 12
Close #PInp
Raw = 1
TotalSamPts = i
n = i
AwNut:
If Err.Number = 62 Then
Dist = SamInt * (i - 1) / 12
Raw = 3
Exit Sub
End If
End If
End Sub
Private Sub Option4_Click()
Dim Inp As Integer, SamInt1
On Error GoTo AwNuts
Dim m, i, K, B4    'Blank
Dim RL, IM, RL1, IM1, RL2() As Single, IM2() As Single, FR2() As Single
Const PI = 3.14159265
Dim l11 As String, m1 As String, D1
Dim Dummy
PInp = FreeFile()
Open (SelectedFile) For Input As #PInp
Line Input #PInp, l11
Line Input #PInp, l11
Input #PInp, B4, ElUnit, NoWPath, SamInt1, DisUnit
If DisUnit = "m" Then
SamInt = SamInt1 * 39.3700787 ' to convert to inches
Else
SamInt = SamInt1
End If
Close #PInp
' to acount for addition info on line 3
Open (SelectedFile) For Input As #PInp
Line Input #PInp, l2
Line Input #PInp, l3
Line Input #PInp, l4
Line Input #PInp, l5
Line Input #PInp, l6
If DisUnit = "m" Then
SamInt = SamInt1 * 39.3700787 ' to convert to inches
Else
SamInt = SamInt1
End If
i = 0
Do
```

```
If Col = 3 Then
Input #PInp, lp(i), RP(i), CO(i)
ElseIf Col = 2 Then
Input #PInp, lp(i), RP(i)
End If
OrPro(i) = RP(i) ' For ploting original profile
i = i + 1
Loop Until EOF(PInp)
Dist = SamInt * (i - 1) / 12
Close #PInp
n = i
TotalSamPts = i
Raw = 2
AwNuts:
If Err.Number = 62 Then
Dist = SamInt * (i - 1)
Raw = 3
Exit Sub
End If
End Sub
Private Sub Option5_Click()
On Error GoTo AwNuts
Dim Inp As Integer, SamInt1, D1
Dim m, i, K, B4    'Blank
Dim RL, IM, RL1, IM1, RL2() As Single, IM2() As Single, FR2() As Single
Const PI = 3.14159265
Dim l11 As String, m1 As String
PInp = FreeFile()
Open (SelectedFile) For Input As #PInp
Line Input #PInp, l11
Line Input #PInp, l11
Input #PInp, B4, ElUnit, NoWPath, SamInt1, DisUnit
If DisUnit = "m" Then
SamInt = SamInt1 * 39.3700787 ' to convert to inches
Else
SamInt = SamInt1
End If
Close #PInp
' to acount for addition info on line 3
Open (SelectedFile) For Input As #PInp
Line Input #PInp, l2
Line Input #PInp, l3
Line Input #PInp, l4
Line Input #PInp, l5
Line Input #PInp, l6
i = 0
Do Until EOF(PInp)
If Col = 3 Then
Input #PInp, lp(i), RP(i), CO(i)
ElseIf Col = 2 Then
Input #PInp, lp(i), RP(i)
End If
AV(i) = ((lp(i) + RP(i)) / 2)
OrPro(i) = AV(i) ' For ploting original profile
i = i + 1
Loop
```

```
Dist = SamInt * (i - 1) / 12
Close #PInp
n = i
TotalSamPts = i
Raw = 3
AwNuts:
If Err.Number = 62 Then
Dist = SamInt * (i - 1)
Raw = 3
Exit Sub
End If
End Sub
Private Sub Option6_Click()
Dim i
Dim POut As Integer
Dim ELStart
Dim ELEnd
Dim NoPointA As Integer
NoPointA = 528 * 12 / SamInt
'ELStart = (Val(Form1.Text8.Text) - 1) * NoPointA
'ELEnd = Val(Form1.Text8.Text) * NoPointA
POut = FreeFile()
Open App.Path & "\Output.txt" For Output As #POut
Print #POut, NoPointA
Print #POut, ElUnit
Print #POut, SamInt
Print #POut, DisUnit
For i = ELStart To ELEnd
Print #1, OrPro(i)
Next i
Close #POut
' IRI input code below
Dim newIRI
Open App.Path & "\Outfile.txt" For Output As #9
Print #9, "10"
Close #9
newIRI = 10
Shell ("ShubIRI.exe")
Do While 10 = newIRI
Open App.Path & "\Outfile.txt" For Input As #4
Input #4, newIRI
Close #4
DoEvents
Loop
Dim ProfileIRI, Inp1
Inp1 = FreeFile()
Open App.Path & "\outfile.txt" For Input As #Inp1
Input #Inp1, ProfileIRI
Close #Inp1
'Form3.Text3.Text = ProfileIRI
End Sub
```

## CODE for Defect.frm (Screen 4)

(Presents data in tabular form, no files needed)

```
Private Sub Command1_Click()
Dim i1 As Integer
Load Form1
Form1.Show
Form18.Hide
MSFlexGrid1.Clear
End Sub
```

## CODE for Graphic.frm (Screen 7)

(Plots original profile, modified profile and profile with defects corrected. Needs no files)

```
Private Sub Command1_Click()
Load Form1
Form1.Show
Form2.Hide
End Sub
Private Sub Command2_Click()
Label8 = "Load in lbs"
Dim xmin As Single, ymin As Single, x1 As Single, y1 As Single, x2 As Single, y2 As Single, x3 As
Single, y3 As Single
Dim xsmallest As Single, jjj As Single, B
Const PI = 3.14159265
Dim scaleincrement, scalevalue
Dim scaleincrement1, scalevalue1
Dim Ysmallest, Ylargest, NoPoint528
NoPoint528 = (528 * 12 / SamInt)
ELStart = (Val(List1.Text) - 1) * NoPoint528
ELEnd = Val(List1.Text) * NoPoint528
xmin = 3200
ymin = 6500
'to write distance on X axis
Me.CurrentX = xmin + 3900
Me.CurrentY = ymin + 250
ForeColor = QBColor(9)
Print "Distance in  feet"; 'DisUnit1
ForeColor = QBColor(0)
' to find the highest and lowest wave value for Y-axis
Ysmallest = 0
Ylargest = 0
For jjj = ELStart To ELEnd
FORCETOTAL1(jjj) = FORCETOTAL(jjj) + Val(Text1.Text)
If FORCETOTAL1(jjj) < Ysmallest Then
Ysmallest = FORCETOTAL1(jjj)
'ElseIf TOTAL(jjj) < Ysmallest Then
'Ysmallest = TOTAL(jjj)
ElseIf FORCETOTAL1(jjj) > Ylargest Then
Ylargest = FORCETOTAL1(jjj)
'ElseIf TOTAL(jjj) > Ylargest Then
'Ylargest = TOTAL(jjj)
End If
Next jjj
'x axis
scaleincrement1 = 8000 / 10
scalevalue1 = 528 / 10
scaleincrement = 0
scalevalue = ELStart * SamInt / 12
For jjj = 0 To 10
x1 = xmin
y1 = ymin
y2 = y1
x2 = x1 + scaleincrement
Line (x1, y1)-(x2, y2), QBColor(9)
Line (x2, ymin - 10)-(x2, ymin + 10)
```

```
' to prevent writing zero on x-axis b'coz it become double with zero from y-axis
If jjj > 0 Then
Me.CurrentX = x2 - 50
Print Format(scalevalue, "#####.##")
End If
scalevalue = scalevalue + scalevalue1
scaleincrement = scaleincrement + scaleincrement1
Next jjj
' y axis
scaleincrement1 = 1000 / 6
If Ysmallest < 0 Then
If Ylargest > -Ysmallest Then
scalevalue1 = Ylargest / 3
Else
scalevalue1 = -Ysmallest / 3
End If
End If
If Ysmallest >= 0 Then
If Ylargest > Ysmallest Then
scalevalue1 = Ylargest / 3
Else
scalevalue1 = -Ysmallest / 3
End If
End If
scaleincrement = 0
scalevalue = 0
For jjj = 0 To 3
x1 = xmin
x2 = x1
y1 = ymin
y2 = y1 - scaleincrement
Line (x1, y1)-(x2, y2), QBColor(9)
Line (xmin - 10, y2)-(xmin + 40, y2)
Me.CurrentX = xmin - 750
Me.CurrentY = y2 - 75
Print Format(scalevalue, "  #######0.00")
scalevalue = scalevalue + scalevalue1
scaleincrement = scaleincrement + scaleincrement1
Next jjj
scaleincrement = 0
scalevalue = 0
For jjj = 0 To 3
x1 = xmin
x2 = x1
y1 = ymin
y2 = y1 + scaleincrement
Line (x1, y1)-(x2, y2), QBColor(9)
'to skip rewriting zero on y-axis
If jjj > 0 Then
Line (xmin - 10, y2)-(xmin + 40, y2)
Me.CurrentX = xmin - 750
Me.CurrentY = y2 - 75
Print Format(scalevalue, " -#######0.00")
End If
scalevalue = scalevalue + scalevalue1
scaleincrement = scaleincrement + scaleincrement1
```

```
Next jjj
Dim jjj1
x1 = xmin
y1 = ymin
x2 = 0
y2 = 0
jjj1 = 0
xsmallest = 8000 / (ELEnd - ELStart)
For jjj = ELStart To ELEnd
x2 = xmin + jjj1 * xsmallest
y2 = ymin - FORCETOTAL1(jjj) * scaleincrement1 / scalevalue1
Line (x1, y1)-(x2, y2), QBColor(2)
x1 = x2
y1 = y2
jjj1 = jjj1 + 1
Next jjj
'to overlap the original Y-axis
x1 = xmin
x2 = x1
y1 = ymin
y2 = y1 - scaleincrement
Line (x1, y1)-(x2, y2), QBColor(9)
Line (xmin - 40, y2)-(xmin + 40, y2)
x1 = xmin
x2 = x1
y1 = ymin
y2 = y1 + scaleincrement
Line (x1, y1)-(x2, y2), QBColor(9)
Line (xmin - 40, y2)-(xmin + 40, y2)
End Sub
Private Sub Command3_Click()
Form2.Cls
End Sub
Private Sub Command4_Click()
Dim Rsp As String
' show save as dialog box
CommonDialog1.ShowSave
'check if file exists,if it does confirm overwrite
If Dir(CommonDialog1.FileName) <> "" Then
Rsp = MsgBox("Overwrite File?", vbYesNoCancel, "File Exists")
If Rsp <> vbYes Then Exit Sub
End If
'open filename for output, use append to add to a file
Open CommonDialog1.FileName For Output As #2
n = (Val(Form1.Text1.Text) * 5280 * 12) / Val(Form1.Text2.Text)
Dim jjj As Integer, ddd, mmm, nnn As Integer
Print #2, "Distance in feet"; "Force in lbs"
For jjj = 1 To n
mmm = jjj * Val(Form1.Text2.Text)
ddd = mmm / 12
FORCETOTAL1(jjj) = FORCETOTAL(jjj) + Val(Text1.Text)
Print #2, Format(ddd, "#######.###"); "       ,    "; Format(FORCETOTAL1(jjj), "#########")
Next jjj
Close #2
End Sub
Private Sub Command7_Click()
```

```
Load Form17
Form17.Show
Form2.Hide
End Sub
Private Sub Command8_Click()
Form2.Cls
End Sub
Private Sub List1_Click()
Form2.Cls
MSFlexGrid1.Clear
Dim xmin As Single, ymin As Single, x1 As Single, y1 As Single, x2 As Single, y2 As Single, x3 As Single, y3 As Single
Dim xsmallest As Single, jjj As Single, B
Const PI = 3.14159265
Dim scaleincrement, scalevalue
Dim scaleincrement1, scalevalue1
Dim Ysmallest, Ylargest, NoPoint528
NoPoint528 = (528 * 12 / SamInt)
Label1 = "Elevation in mils"
ELStart = (Val(List1.Text) - 1) * NoPoint528
ELEnd = Val(List1.Text) * NoPoint528
If Val(List1.Text) = ToNoSec Then
NoPoint528 = (LlastSec * 12 / SamInt)
ELStart = (Val(List1.Text) - 1) * (528 * 12 / SamInt)
ELEnd = ELStart + NoPoint528
End If
xmin = 3200
ymin = 3000
'to write distance on X axis
Me.CurrentX = xmin + 3900
Me.CurrentY = ymin + 250
ForeColor = QBColor(9)
Print "Distance in  feet"; 'DisUnit1
ForeColor = QBColor(0)
' to find the highest and lowest wave value for Y-axis
Ysmallest = 0
Ylargest = 0
For jjj = ELStart To ELEnd
If OrPro1(jjj) < Ysmallest Then
Ysmallest = OrPro1(jjj)
'ElseIf TOTAL(jjj) < Ysmallest Then
'Ysmallest = TOTAL(jjj)
ElseIf OrPro1(jjj) > Ylargest Then
Ylargest = OrPro1(jjj)
'ElseIf TOTAL(jjj) > Ylargest Then
'Ylargest = TOTAL(jjj)
End If
Next jjj
'x axis
scaleincrement1 = 8000 / 10
scalevalue1 = 528 / 10
If Val(List1.Text) = ToNoSec Then
scalevalue1 = LlastSec / 10
End If
scaleincrement = 0
scalevalue = ELStart * SamInt / 12
```

```
For jjj = 0 To 10
x1 = xmin
y1 = ymin
y2 = y1
x2 = x1 + scaleincrement
Line (x1, y1)-(x2, y2), QBColor(9)
Line (x2, ymin - 10)-(x2, ymin + 10)
' to prevent writing zero on x-axis b'coz it become double with zero from y-axis
If jjj > 0 Then
Me.CurrentX = x2 - 50
Print Format(scalevalue, "#####.##")
End If
scalevalue = scalevalue + scalevalue1
scaleincrement = scaleincrement + scaleincrement1
Next jjj
' y axis
scaleincrement1 = 4000 / 10
If Ysmallest < 0 Then
If Ylargest > -Ysmallest Then
scalevalue1 = Ylargest / 5
Else
scalevalue1 = -Ysmallest / 5
End If
End If
If Ysmallest >= 0 Then
If Ylargest > Ysmallest Then
scalevalue1 = Ylargest / 5
Else
scalevalue1 = -Ysmallest / 5
End If
End If
scaleincrement = 0
scalevalue = 0
For jjj = 0 To 5
x1 = xmin
x2 = x1
y1 = ymin
y2 = y1 - scaleincrement
Line (x1, y1)-(x2, y2), QBColor(9)
Line (xmin - 10, y2)-(xmin + 40, y2)
Me.CurrentX = xmin - 750
Me.CurrentY = y2 - 75
Print Format(scalevalue, "  #######0.00")
scalevalue = scalevalue + scalevalue1
scaleincrement = scaleincrement + scaleincrement1
Next jjj
scaleincrement = 0
scalevalue = 0
For jjj = 0 To 5
x1 = xmin
x2 = x1
y1 = ymin
y2 = y1 + scaleincrement
Line (x1, y1)-(x2, y2), QBColor(9)
'to skip rewriting zero on y-axis
If jjj > 0 Then
```

```
Line (xmin - 10, y2)-(xmin + 40, y2)
Me.CurrentX = xmin - 750
Me.CurrentY = y2 - 75
Print Format(scalevalue, " -#######0.00")
End If
scalevalue = scalevalue + scalevalue1
scaleincrement = scaleincrement + scaleincrement1
Next jjj
Dim jjj1, jjj3, y7, y8, y9, y10
x1 = xmin
y1 = ymin
x2 = 0
y2 = 0
y7 = ymin
y8 = 0
y9 = 0
y10 = ymin
jjj1 = 0
jjj3 = 1
xsmallest = 8000 / (ELEnd - ELStart)
For jjj = ELStart To ELEnd
DrawWidth = 1
x2 = xmin + jjj1 * xsmallest
y10 = ymin - FINALTOTAL1(jjj) * scaleincrement1 / scalevalue1
Line (x1, y9)-(x2, y10), QBColor(14)
DrawWidth = 1.2
y8 = ymin - TOTALBUMP1(jjj) * scaleincrement1 / scalevalue1
Line (x1, y7)-(x2, y8), QBColor(12)
DrawWidth = 1.1
y2 = ymin - OrPro1(jjj) * scaleincrement1 / scalevalue1
Line (x1, y1)-(x2, y2), QBColor(2)
For jjj2 = 1 To NoBumbsform2
If jjj = ELBUMPNO(jjj2) Then
Me.Circle (x2, y2), 50, QBColor(12)
Me.FillStyle = 0
Me.FillColor = QBColor(12)
Form2.MSFlexGrid1.TextMatrix(jjj3, 0) = Format(ELBUMPNO(jjj2) * SamInt / 12, "#######0.00")
Form2.MSFlexGrid1.TextMatrix(jjj3, 1) = Format(ELBUMPHT(jjj2), "#######0.00")
Form2.MSFlexGrid1.TextMatrix(jjj3, 2) = Format(ELBUMPBIGNG(jjj2), "#######0.00")
Form2.MSFlexGrid1.TextMatrix(jjj3, 3) = Format(ELBUMPEND(jjj2), "#######0.00")
 jjj3 = jjj3 + 1
End If
Form2.MSFlexGrid1.Rows = jjj3 + 3
Next jjj2
x1 = x2
y1 = y2
y7 = y8
y9 = y10
jjj1 = jjj1 + 1
Next jjj
'to overlap the original Y-axis
x1 = xmin
x2 = x1
y1 = ymin
y2 = y1 - scaleincrement
Line (x1, y1)-(x2, y2), QBColor(9)
```

```
Line (xmin - 40, y2)-(xmin + 40, y2)
x1 = xmin
x2 = x1
y1 = ymin
y2 = y1 + scaleincrement
Line (x1, y1)-(x2, y2), QBColor(9)
Line (xmin - 40, y2)-(xmin + 40, y2)
"""to fill in the ms flexgrid
MSFlexGrid1.TextMatrix(0, 0) = "Loc(ft)"
MSFlexGrid1.TextMatrix(0, 1) = "Ht(Mils)"
"'to fill in iri and psi
Text8.Text = PIRI(Val(List1.Text))
Text9.Text = PPSI(Val(List1.Text))
Text7.Text = BIRI(Val(List1.Text))
Text10.Text = BPSI(Val(List1.Text))
End Sub
```

## CODE for Dynamic Transfer form (Screen 8)

(Calculates predicted dynamic load transfer function for a quarter truck model, calculates dynamic load on pavement)

```
Dim a23(100000), b23(100000), c23(100000), d23(100000), w23(100000), ra23(100000), ima23(100000), RF(100000), IMF(100000)
Dim FRL(100000), FIMG(100000), FRT(100000), w2323(100000)
Dim ra2323(100000), ima2323(100000), n
Const PI = 3.14159265
Private Sub Command1_Click()
Label10 = "Force in lbs/in"
Load Form25
Form25.Show
Form25.Refresh
Form26.Cls
Dim k1, k2, u, C, sp, kt
k1 = Val(Text1.Text)
k2 = Val(Text2.Text)
u = Val(Text3.Text)
C = Val(Text4.Text)
kt = Val(Text5.Text)
Dim m, Offset21
n = (Val(Form1.Text1.Text) * 5280 * 12) / Val(Form1.Text2.Text)
Dim dis As Integer
dis = 528 * 12 / SamInt
ReDim FR2(5 + dis / 2)
For i = 1 To dis / 2
FR2(i) = i / (SamInt * (dis))
w23(i) = FR2(i) * 866 * (2 * PI) ' to convert to radians
w2323(i) = FR2(i) * 866 ' to convert to hz
a23(i) = (2 * k2 * w23(i) * w23(i) * kt) - (kt * w23(i) * w23(i) * w23(i) * w23(i))
b23(i) = 2 * kt * C * w23(i) * w23(i) * w23(i)
c23(i) = (k1 * k2) - (k1 * w23(i) * w23(i)) - (k2 * u * w23(i) * w23(i)) - (k2 * w23(i) * w23(i)) + (u * w23(i) * w23(i) * w23(i) * w23(i))
d23(i) = (k1 * C * w23(i)) - (u * C * w23(i) * w23(i) * w23(i)) - (C * w23(i) * w23(i) * w23(i))
RF(i) = ((a23(i) * c23(i) + b23(i) * d23(i)) / ((c23(i) * c23(i)) + (d23(i) * d23(i)))) '+ 8850) / 8850
IMF(i) = ((b23(i) * c23(i) - a23(i) * d23(i)) / ((c23(i) * c23(i)) + (d23(i) * d23(i)))) ' + 8850) / 8850
FRT(i) = ((IMF(i) * IMF(i) + RF(i) * RF(i)) ^ 0.5)
Next i
Dim xmin As Single, ymin As Single, x1 As Single, y1 As Single, x2 As Single, y2 As Single, x3 As Single, y3 As Single
Dim xsmallest As Single, jjj As Single, B
Dim scaleincrement, scalevalue
Dim scaleincrement1, scalevalue1
Dim Ysmallest, Ylargest
xmin = 4200
ymin = 3000
'to write distance on X axis
Me.CurrentX = xmin + 3900
Me.CurrentY = ymin + 250
ForeColor = QBColor(9)
Print "Frequency in Hz"; 'DisUnit1
ForeColor = QBColor(0)
' to find the highest and lowest wave value for Y-axis
Ysmallest = 0
Ylargest = 0
```

```
For jjj = 0 To i
If FRT(jjj) < Ysmallest Then
Ysmallest = FRT(jjj)
ElseIf FRT(jjj) > Ylargest Then
Ylargest = FRT(jjj)
End If
Next jjj
Dim Lastm
Lastm = i - 1
'x axis
scaleincrement1 = 8000 / 10
scalevalue1 = w2323(Lastm) / 10
scaleincrement = 0
scalevalue = 0
For jjj = 0 To 10
x1 = xmin
y1 = ymin
y2 = y1
x2 = x1 + scaleincrement
Line (x1, y1)-(x2, y2), QBColor(9)
Line (x2, ymin - 10)-(x2, ymin + 10)
' to prevent writing zero on x-axis b'coz it become double with zero from y-axis
If jjj > 0 Then
Me.CurrentX = x2 - 50
Print Format(scalevalue, "#####.##")
End If
scalevalue = scalevalue + scalevalue1
scaleincrement = scaleincrement + scaleincrement1
Next jjj
' y axis
scaleincrement1 = 4000 / 10
If Ysmallest < 0 Then
If Ylargest > -Ysmallest Then
scalevalue1 = Ylargest / 5
Else
scalevalue1 = -Ysmallest / 5
End If
End If
If Ysmallest >= 0 Then
If Ylargest > Ysmallest Then
scalevalue1 = Ylargest / 5
Else
scalevalue1 = -Ysmallest / 5
End If
End If
scaleincrement = 0
scalevalue = 0
For jjj = 0 To 5
x1 = xmin
x2 = x1
y1 = ymin
y2 = y1 - scaleincrement
Line (x1, y1)-(x2, y2), QBColor(9)
Line (xmin - 10, y2)-(xmin + 40, y2)
Me.CurrentX = xmin - 750
Me.CurrentY = y2 - 75
```

```
Print Format(scalevalue, "  #######0.00")
scalevalue = scalevalue + scalevalue1
scaleincrement = scaleincrement + scaleincrement1

Next jjj
scaleincrement = 0
scalevalue = 0
For jjj = 0 To 5
x1 = xmin
x2 = x1
y1 = ymin
y2 = y1 + scaleincrement
Line (x1, y1)-(x2, y2), QBColor(9)
'to skip rewriting zero on y-axis
If jjj > 0 Then
Line (xmin - 10, y2)-(xmin + 40, y2)
Me.CurrentX = xmin - 750
Me.CurrentY = y2 - 75
Print Format(scalevalue, " -#######0.00")
End If
scalevalue = scalevalue + scalevalue1
scaleincrement = scaleincrement + scaleincrement1
Next jjj
x1 = xmin
y1 = ymin
x2 = 0
y2 = 0
xsmallest = 8000 / i
For jjj = 0 To i
x2 = xmin + jjj * xsmallest
y2 = ymin - FRT(jjj) * scaleincrement1 / scalevalue1
Line (x1, y1)-(x2, y2), QBColor(2)
x1 = x2
y1 = y2
Next jjj
'to overlap the original Y-axis
x1 = xmin
x2 = x1
y1 = ymin
y2 = y1 - scaleincrement
Line (x1, y1)-(x2, y2), QBColor(9)
Line (xmin - 40, y2)-(xmin + 40, y2)
x1 = xmin
x2 = x1
y1 = ymin
y2 = y1 + scaleincrement
Line (x1, y1)-(x2, y2), QBColor(9)
Line (xmin - 40, y2)-(xmin + 40, y2)
Unload Form25
End Sub
Private Sub Command2_Click()
Load Form25
Form25.Show
Form25.Refresh
Const PI = 3.14159265
Dim m, Offset21
```

```
NoPoint10 = 0 ' 12.5 * 12 / SamInt
NoPoint528 = (528 * 12 / SamInt)
For j = 1 To Val(Form1.Text3.Text)
If j = 1 Then
NoPointDFT = NoPoint10 + NoPoint528
Else
NoPointDFT = 2 * NoPoint10 + NoPoint528
End If
ReDim RL2(NoPointDFT / 2), IM2(NoPointDFT / 2), FR2(NoPointDFT / 2)
ELStart = (j - 1) * NoPoint528
ELEnd = j * NoPoint528
If j = 1 Then
ELStart1 = ELStart
Else
ELStart1 = ELStart - NoPoint10
End If
ELEnd1 = ELEnd + NoPoint10
For m = 0 To NoPointDFT / 2
RL = 0
IM = 0
RL1 = 0
IM1 = 0
Dim k1
k1 = 0
For K = ELStart1 To ELEnd1 - 1
RL = OrPro1(K) * Cos(2 * PI * m * k1 / NoPointDFT)
IM = OrPro1(K) * Sin(2 * PI * m * k1 / NoPointDFT)
RL1 = RL1 + RL
IM1 = IM1 + IM
k1 = k1 + 1
Next K
If m = 0 Then
RL2(m) = RL1 / NoPointDFT
IM2(m) = IM1 / NoPointDFT
FR2(m) = m / (SamInt * NoPointDFT)
Offset21 = RL2(m)
Else
RL2(m) = 2 * RL1 / NoPointDFT
IM2(m) = 2 * IM1 / NoPointDFT
FR2(m) = m / (SamInt * NoPointDFT)
End If
ra23(m) = RL2(m) / 1000 ' to convert to inches
ima23(m) = IM2(m) / 1000 ' to convert to inches
Next m
NoFreq1 = m ' to be used with cos and sine commond on form 1
noofpoints = m  ' to be used in bump form and also for modifyinput in form 1(profile form
'MSFlexGrid1.Rows = m + 50
'%%%%%%%%%%%%%%%%%%%DFT
Dim XK As Single, XK1 As Single
Dim i%, j1 As Long
n = ELEnd1 - ELStart1 + 1
Interval = Val(Form1.Text2.Text)
m1 = m
m123 = m
'Calculating Profile
B = 0
```

```
For j1 = 0 To n
XK1 = 0
XK = 0
For i = 1 To m - 1
FRL(i) = (RF(i) * ra23(i) - IMF(i) * ima23(i))
FIMG(i) = (RF(i) * ima23(i) + IMF(i) * ra23(i))
XK = FRL(i) * Cos(2 * PI * i * j1 / n) + FIMG(i) * Sin(2 * PI * i * j1 / n)
XK1 = XK1 + XK
Next i
TOTAL(j1) = XK1' + RL2(0)
Next j1
If j = 1 Then
K = 0
Else
K = NoPoint10
End If
For j1 = ELStart To ELEnd
FORCETOTAL(j1) = TOTAL(K)
K = K + 1
Next j1
Next j
Unload Form25
End Sub
Private Sub Command4_Click()
Form2.Text1.Text = (Val(Text10.Text) + Val(Text11.Text)) * 32 * 12
Load Form1
Form1.Show
Form26.Hide
End Sub
Private Sub Command5_Click()
Text1.Text = Val(Text9.Text) / Val(Text11.Text)
Text2.Text = Val(Text5.Text) / Val(Text11.Text)
Text3.Text = Val(Text10.Text) / Val(Text11.Text)
Text4.Text = Val(Text8.Text) / Val(Text11.Text)
End Sub
```

# VITA

The author, Shubham Rawool, was born in Goa, a small state on the west coast of India, to Shivaji Rawool and Shubhada Rawool.

After graduating with honors from Goa College of Engineering, Farmagudi-Goa, with a degree in civil engineering, the author worked with M.C. Bauchemie India Ltd and The Associated Cement Companies India Ltd. (ACC).

He joined Texas A&M University, College Station, Texas, in the Fall of 2001 to pursue a master's degree in civil engineering. Since then he has been working as a research assistant at Texas Transportation Institute (TTI). The author has always been among the top students during his academics and will be initiated in *The Honor Society of Phi Kappa Phi* in April 2004 for his academic achievements at Texas A&M University.

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